

Gravestone Guardians Technical Paper No. 3

Structural Adhesives in Historic Marble Monument Repair

Strength, Stiffness, Failure Hierarchy, and Limited-Bond Reassembly Systems

Evaluating Epoxies, Putties, Acrylics, Mineral Grouts, and Setting Materials for Conservation-Oriented Monument Repair

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Gravestone Guardians, Inc.

A 501(c)(3) nonprofit organization dedicated to the preservation, documentation, restoration, and interpretation of historic cemeteries through education, research, and hands-on conservation.

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Disclaimer

This technical paper is intended to contribute to the discussion surrounding the conservation and repair of historic marble grave markers, monuments, and related cemetery structures. It synthesizes published conservation literature, materials-science research, manufacturer technical information, monument-industry practice, and field observations relevant to the selection and use of structural adhesives and associated setting materials.

The paper is not an engineering standard, regulatory document, product endorsement, or substitute for project-specific professional judgment. Historic monuments vary substantially in material composition, condition, geometry, previous treatment, structural configuration, environmental exposure, and cultural significance. A material or repair method considered appropriate for one monument may be inappropriate for another.

Structural instability can present serious hazards. Large, elevated, mechanically complex, severely deteriorated, or otherwise hazardous monuments should be evaluated by practitioners with appropriate conservation, masonry, engineering, rigging, or monument-setting expertise. Applicable cemetery rules, property-owner requirements, occupational safety requirements, historic-preservation regulations, and local laws should be followed.

Product names appearing in this paper, including AKEPOX 5010, Pratley Standard Setting Putty, Tenax Domo 10, HXTAL NYL-1, Paraloid B-72, Paraloid B-48N, and other commercial materials, are included for technical comparison and discussion. Their inclusion does not constitute an endorsement by Gravestone Guardians, Inc. Manufacturer formulations, specifications, and recommended uses may change, and current technical data should be reviewed before use.

The experimental concepts and treatment frameworks proposed in later sections of this paper should be understood as subjects for further evaluation rather than universally validated treatment standards.

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Abstract

The reassembly of broken and dismantled historic marble monuments presents a persistent conservation problem. Structural adhesives must provide sufficient resistance to separation, shear, impact, and environmental movement while avoiding unnecessary alteration or loss of original stone. Modern epoxies and epoxy putties can provide exceptional strength and durability, but these same characteristics have generated longstanding concerns within conservation practice. A frequently repeated principle holds that a repair material should be weaker than the historic stone so that, when a repaired assembly is overloaded, failure occurs within the repair rather than within original material. Although this principle expresses an important conservation objective, adhesive selection based principally upon tensile strength provides an incomplete description of the mechanical behavior of a repaired monument.

Adhesive performance is governed by the interaction of multiple properties and conditions, including elastic modulus, fracture toughness, bond-line thickness, bonded surface area, joint geometry, load direction, substrate condition, thermal and moisture movement, adhesive aging, workmanship, and the location at which eventual failure occurs. Published conservation testing further demonstrates that adhesive systems considered comparatively reversible, including acrylic thermoplastics such as Paraloid B-72, can in some configurations produce marble-to-marble assemblies that fail within the stone rather than at the adhesive interface. Conversely, the use of a high-strength adhesive does not necessarily require the adhesive to carry the entire structural load of an assembled monument (Jorjani et al., 2008).

This paper therefore proposes that the conservation suitability of an adhesive cannot be determined from adhesive strength alone. Instead, the monument and its repair should be evaluated as a coupled structural system in which bearing, restraint, bonding, sealing, and weather protection may be performed by different materials. Particular attention is given to what this paper terms **limited-bond reassembly**: the deliberate use of localized quantities of structural adhesive within an assembly whose primary dead load is carried through stable stone-to-stone or stone-to-bearing-material compression rather than through a continuous adhesive layer.

This framework is examined in relation to several material families used in historic stone repair and monument setting, including structural epoxies, epoxy putties, polyester mastics, acrylic thermoplastics, intervention-layer systems, mineral grouts, lead wedges, and monument setting compounds. Particular consideration is given to Akepox 5010 for closely fitted marble fractures and to Pratley Standard Setting Putty used as localized restraint in multi-piece monument reassembly. Tenax Domo 10 and other high-strength

fabrication adhesives provide useful comparisons because commercial stone fabrication frequently values maximum permanent bond strength, whereas conservation practice must also consider future failure, retreatment, original-material loss, and the consequences of making the repaired interface substantially different from surrounding weathered stone.

The paper advances the concept of **failure hierarchy** as a more useful framework than a simple requirement that the adhesive be weaker than the stone. A conservation-oriented repair should seek not merely adequate strength but a predictable and minimally destructive response to future overload, deterioration, or treatment. This may be accomplished through material selection, controlled bonded area, joint design, appropriate bearing, avoidance of unnecessary drilling, accessible perimeter joints, and documentation of permanent interventions.

An experimental program is ultimately proposed in which adhesive systems are evaluated not only according to maximum load capacity but also according to stiffness, displacement, environmental durability, failure location, fracture propagation, original stone loss, and practical retreatability. Such evaluation is particularly important because much of the existing conservation research was conducted using relatively sound marble under controlled laboratory conditions rather than naturally weathered nineteenth-century cemetery marble subject to decades of freeze-thaw cycling, thermal movement, moisture, biological growth, and previous repair.

The principal argument of this paper is therefore not that strong structural adhesives are inherently appropriate for historic marble, nor that traditional conservation concerns regarding permanent adhesives are misplaced. Rather, adhesive strength must be understood as one component of a larger treatment system. The objective should be to provide the minimum structural intervention necessary while designing the assembly around the least damaging reasonably foreseeable failure mode.

Executive Summary

Historic marble monument repair occupies an uncomfortable space between structural necessity and conservation restraint. Broken tablets must sometimes be rejoined. Multi-piece monuments that have been dismantled, displaced, or destabilized must sometimes be reassembled. Loose upper sections may require resistance to sliding or accidental displacement. At the same time, every permanent intervention introduces material that was not originally part of the monument and may influence how the stone responds to future loads, environmental movement, deterioration, and eventual retreatment.

Modern structural adhesives are particularly controversial because they can be substantially stronger and less reversible than the weathered marble to which they are applied. Epoxy systems developed for stone fabrication are commonly marketed according to high bond strength, durability, chemical resistance, low shrinkage, and the ability to create a joint that approaches or exceeds the strength of the stone. Those qualities are desirable when permanent fabrication is the principal objective. In conservation, however, a bond that survives by causing the historic substrate to fracture may represent an undesirable failure hierarchy.

This concern has sometimes been condensed into the rule that an adhesive used on historic stone should be weaker than the stone itself. The objective behind that rule is sound: if future failure is unavoidable, the treatment material should ideally surrender before significant original material is lost. The difficulty is that neither the adhesive nor the stone can be adequately described by a single strength value. Weathered marble is heterogeneous, anisotropic, microcracked, and environmentally responsive. Its mechanical condition may differ considerably within a single monument. Calcite crystals exhibit anisotropic thermal expansion, and repeated environmental cycling can contribute to intergranular microcracking and gradual loss of cohesion. Consequently, the properties of an unweathered laboratory marble specimen cannot automatically be assumed to describe a century-old exterior grave marker (Siegesmund et al., 2000).

The adhesive presents similar complexity. Manufacturer-reported tensile strength describes a material tested under specified conditions; it does not independently predict the behavior of an actual historic-stone joint. The resulting assembly also depends upon the stiffness of the cured resin, its ability to accommodate deformation, its adhesion to the particular stone surface, bond-line thickness, joint geometry, bonded area, and the direction and duration of the load. A comparatively strong but less stiff adhesive used in a very small area may produce a different risk profile from a nominally weaker but much stiffer adhesive applied continuously across a broad interface.

Conservation testing illustrates the problem. Podany, Garland, Freeman, and Rogers examined Paraloid B-72, epoxy, polyester, and combinations employing B-72 as an intervention layer between marble and structural adhesive. In their testing, conventional epoxy and polyester joints failed within the marble rather than through the adhesive. More unexpectedly, most B-72 specimens also failed within the marble during tensile testing. The results demonstrated that even an adhesive favored in conservation because of its solubility and potential retreatability may produce a joint sufficiently strong that failure migrates into the stone. Later testing by Jorjani and colleagues likewise found several thermoplastic systems mechanically viable for marble repair and emphasized interfacial fracture toughness and bond-line dimensions rather than treating bulk adhesive strength as the sole determinant of performance (Jorjani et al., 2008; Podany et al., 2001).

These findings do not invalidate the conservation preference for reversible or retreatable materials. They instead demonstrate that the desired outcome—protecting original stone during future failure—cannot be assured merely by selecting a resin conventionally classified as reversible or comparatively weak.

The present paper develops **failure hierarchy** as a broader treatment principle. Failure hierarchy asks where damage is expected to occur when the repaired monument is subjected to forces beyond those anticipated in normal service. The preferred hierarchy will depend upon the monument, but a conservation-oriented system generally seeks to direct deterioration or eventual failure toward replaceable or localized treatment materials rather than irreplaceable historic fabric.

This perspective is particularly relevant to multi-piece monuments. A stacked marble monument in good geometric contact does not necessarily require a continuous adhesive film to carry its dead load. Much of that load can and should remain compressive, passing downward through stone interfaces and appropriately designed bearing points. Lead wedges or other suitable bearing materials can establish alignment and distribute contact. A localized adhesive may then provide restraint against sliding, separation, or accidental disturbance, while a perimeter setting compound or compatible joint material performs a different function associated with weather protection and joint closure.

Under this arrangement, the adhesive is intentionally denied the opportunity to become the sole structural system. Its inherent tensile or shear strength may remain high, but the force it can transmit to the monument is influenced by the amount of adhesive present, the area bonded, its location, and the geometry of the assembly. This paper refers to that approach as a **limited-bond reassembly system**.

Gravestone Guardians currently employs different adhesive strategies according to the repair problem. Closely fitted tablet fractures are typically rejoined using Akepox 5010 as the primary structural adhesive. Multi-piece monument assemblies may instead employ localized Pratley Standard Setting Putty in conjunction with lead wedges and monument setting compound, reducing reliance upon either internal drilling and pinning or continuous full-surface epoxy bonding. This paper does not assume that either practice is inherently correct. Rather, these methods provide practical case studies through which the competing principles of strength, permanence, restraint, bearing, retreatability, and future failure can be evaluated.

The distinction is important because the alternative to permanent adhesive is not always a benign reversible repair. Mechanical pinning requires drilling original stone, removes historic fabric, creates holes that ordinarily cannot be returned to their pre-treatment condition, and establishes concentrated load-transfer zones around rigid reinforcement. As examined in Gravestone Guardians Technical Paper No. 2, pinning may be entirely justified where structural loads require reinforcement, but it should not be treated as an automatic conservation upgrade simply because adhesives are permanent.

The goal of Technical Paper No. 3 is therefore not to establish a preferred commercial product. It is to develop a decision framework capable of distinguishing between different repair situations and different material functions. Structural adhesive, gap filler, bearing pad, pointing material, perimeter seal, reinforcement, and injection grout should not be treated as interchangeable categories simply because each can contribute to holding a monument together.

The framework developed throughout this paper rests on several propositions:

1. **Adequate strength is necessary, but maximum strength is not the objective of conservation repair.**
2. **Adhesive tensile strength alone cannot establish compatibility with historic marble.** Stiffness, fracture behavior, geometry, bonded area, environmental response, and substrate condition must also be considered.
3. **The location and consequences of eventual failure are conservation properties.** A joint that sustains a greater laboratory load but removes substantially more original stone when it fails may be less desirable than a lower-capacity system with a controlled and retreatable failure mode.
4. **Bearing and bonding should be treated as separate structural functions where monument geometry permits.** Gravity and compression can frequently carry dead load more appropriately than a continuous polymer adhesive layer.

5. **Permanence exists on a spectrum of practical retreatability rather than as a simple reversible/irreversible binary.** A permanent material used in small, documented, accessible locations may present a different future-treatment burden from the same material applied over an entire stone interface.
6. **The least invasive adequate system should be preferred.** In some cases, this may involve no adhesive; in others, a thermoplastic adhesive, mineral material, localized epoxy, epoxy putty, mechanical reinforcement, or a combined system may be justified.

Current professional conservation ethics support this type of contextual evaluation. The American Institute for Conservation directs practitioners to select materials and methods appropriate to the specific treatment while balancing their benefits against potential adverse effects on future examination, treatment, and function. Earlier scholarship on reversibility likewise recognized that reversibility exists by degree and that even interventions that cannot be completely reversed should be examined according to their capacity to permit future treatment or retreatment (American Institute for Conservation, n.d.; Appelbaum, 1987).

Technical Paper No. 3 accordingly seeks a middle position between two inadequate absolutes. The first is that modern high-strength adhesives should be avoided simply because they are stronger than historic marble. The second is that an adhesive is appropriate whenever it produces a durable bond. Neither adequately describes conservation practice.

A better objective is to understand the monument, define the structural function that must be restored, select the least invasive materials capable of performing that function, limit permanent intervention to the amount actually required, and consider before treatment what will happen when the repair eventually reaches the end of its useful life.

Key Findings and Working Propositions

The evidence reviewed at the outset of this study supports several preliminary findings that will be examined in greater detail throughout the paper.

- A structural adhesive cannot be judged by tensile strength alone. Elastic modulus, fracture toughness, bond geometry, bonded area, substrate condition, environmental exposure, and failure location materially influence performance.

- The common conservation objective that a repair should fail before the historic stone is conceptually useful but cannot reliably be achieved merely by choosing an adhesive classified as weak or reversible. Laboratory marble assemblies bonded with Paraloid B-72 have, under some test configurations, failed within the marble rather than at the adhesive interface (Podany et al., 2001).
- Full-surface structural bonding and localized adhesive restraint are mechanically different interventions even when the same adhesive is used. Reducing bonded area can limit the amount and distribution of force transmitted through a permanent adhesive system.
- Stable bearing should carry monument dead load wherever monument geometry permits. Adhesives should not be required to substitute for inadequate support, unstable foundations, improper alignment, or deficient bearing.
- Reversibility should be evaluated in practical terms. Solubility of an adhesive does not guarantee that a completed stone treatment can be reversed without damage, while limited use of a permanent adhesive does not necessarily make an entire monument assembly impossible to retreat.
- The preferred repair is not necessarily the strongest available system. The appropriate system is the one that provides adequate stability while minimizing the probability and consequence of damage to original historic material.

Key Terms

Term	Working Definition Used in This Paper
Adhesive failure	Separation occurring primarily at the interface between the adhesive and the stone substrate.
Bonded area	The portion of the stone interface over which adhesive forms an effective mechanical bond.
Bond line	The cured adhesive layer existing between two joined surfaces.
Cohesive adhesive failure	Failure occurring within the body of the cured adhesive rather than at the adhesive-stone interface.
Cohesive stone failure	Fracture or material loss occurring within the historic stone while the adhesive bond remains substantially intact.
Elastic modulus	A measure of the stiffness of a material; broadly, its resistance to elastic deformation under load.

Term	Working Definition Used in This Paper
Failure hierarchy	The intended or observed sequence and location of failure among the components of a repaired assembly when loads exceed its capacity.
Fracture toughness	The ability of a material or bonded interface to resist initiation and propagation of a crack.
Limited-bond reassembly	A repair strategy in which structural adhesive is deliberately confined to selected locations or reduced bonded areas while other components of the assembly carry primary bearing and compressive loads.
Mechanical reinforcement	Pins, dowels, anchors, cramps, or related components that transfer structural loads through mechanical engagement with the stone.
Reversibility	The degree to which the effects of a treatment can be undone without unacceptable alteration or damage to the historic material.
Retreatability	The practical ability to modify, remove, replace, or work around a previous treatment during a future conservation intervention.
Structural adhesive	An adhesive intended to transfer meaningful mechanical loads between joined components.
System-level sacrificiality	A repair design in which replaceable materials, limited interfaces, or accessible components are deliberately arranged to experience deterioration or failure preferentially to irreplaceable historic material.
Tensile strength	The maximum tensile stress a material can sustain under the conditions of a particular test before failure.

1. Introduction

1.1. The Problem of Joining Historic Stone

A broken historic marble monument presents a deceptively simple question: how should the pieces be put back together? In practical cemetery work, the answer may involve adhesive, mortar, grout, lead, mechanical reinforcement, setting compound, gravity, friction, or some combination of these. The apparent simplicity disappears once the consequences of the repair are considered. A joint must remain sufficiently stable for the monument to function safely in an exterior environment, yet the means by which that stability is achieved can alter where and how the monument eventually fails.

This tension has accompanied the use of synthetic adhesives in conservation for decades. Modern epoxies offer properties that earlier natural adhesives could not reliably provide: high structural strength, low shrinkage, moisture resistance, chemical stability, gap-filling capacity, and predictable curing. Their usefulness in repairing broken stone is well established, and the National Park Service includes epoxy repair among recognized treatments for reattaching broken stone and architectural details. The Getty Conservation Institute has likewise documented the extensive history of epoxy resin use in stone conservation while also examining the problems that can arise when polymer treatments interact poorly with porous and deteriorated stone (Grimmer, 1984; Selwitz, 1992).

The same permanence that makes epoxy attractive as an engineering material creates difficulty from a conservation perspective. An adhesive manufacturer typically seeks reliable adhesion, durability, resistance to environmental exposure, and a bond that does not intentionally release. The conservator must consider those same characteristics together with a different set of questions. Can the treatment be removed or modified in the future? What happens if the monument moves? Will a rigid bonded region behave differently from adjacent weathered stone? If the assembly is overloaded, will the adhesive release, or will original stone break around it? Will the next practitioner be able to distinguish and access the repair? These concerns do not make structural adhesives inappropriate by definition, but they change the criteria by which their success should be judged.

Podany and colleagues described this difference directly when examining structural adhesives for large marble sculptures. Conservation requires adequate bond strength and long-term stability, but it also values the ability to undo or retreat a repair—an objective generally absent from commercial adhesive design. Their work is particularly relevant because it did not treat reversibility and strength as mutually exclusive concepts. Instead,

it tested whether Paraloid B-72 could provide useful structural adhesion by itself or act as an intervention layer beneath stronger epoxy and polyester adhesives (Podany et al., 2001).

Historic cemetery monuments complicate the question further because they exist in an environment fundamentally different from a museum gallery. Exterior marble experiences daily and seasonal temperature changes, wetting and drying, freeze-thaw exposure in cold climates, biological colonization, precipitation, ground movement, and occasional impact or vandalism. Many surviving nineteenth-century marble markers have already undergone substantial physical weathering before repair begins. The repair is therefore joining not ideal engineering material but an aged and frequently heterogeneous stone whose mechanical capacity may be markedly different at the surface, within the fracture zone, and in the relatively protected interior.

For marble, this aging is especially important. Calcite exhibits pronounced anisotropic thermal expansion: its dimensional response depends upon crystallographic direction. Because marble is an aggregate of differently oriented calcite crystals, repeated thermal cycling can generate incompatibility at grain boundaries, promote microcracking, and gradually reduce intergranular cohesion. Rock fabric, grain size, orientation, pre-existing cracks, moisture, and environmental history all influence the severity of this deterioration. The familiar conservation description of a marble surface as “sugaring” is therefore not merely cosmetic; at advanced stages it represents a weakening of the stone fabric that directly affects the ability of that fabric to receive and redistribute loads from a repair (Siegesmund et al., 2000).

Consequently, the question “Which adhesive is strongest?” is of limited value in historic marble repair. A more appropriate inquiry is whether the combined stone-and-repair system possesses enough capacity for its intended service while avoiding unnecessary concentration of force in the weakest portions of the monument.

1.2. Conservation and Fabrication Pursue Different Forms of Success

The modern stone industry has developed excellent adhesives for assembling newly quarried marble, granite, engineered stone, and architectural components. Within that context, high adhesion and substrate-breaking strength can legitimately demonstrate product performance. When relatively sound new stone is being fabricated into a permanent assembly, the expectation that the joint should remain intact for the useful life of the product is rational.

Historic conservation measures success differently. The original stone itself is irreplaceable, while virtually every repair material is replaceable in principle, if not always easily in practice. A repair that remains visually intact while transferring an overload several

centimeters into historic marble may therefore be less satisfactory than a repair that releases at a lower force but confines damage to the treatment interface. Maximum bond strength and maximum preservation are not necessarily the same objective.

This difference should not be exaggerated into a conflict between “industry” and “conservation.” Monument setters, stone fabricators, structural engineers, conservators, and cemetery preservationists confront overlapping practical concerns and have accumulated useful experience within different working environments. The problem arises when performance criteria developed for one context are transferred to another without examining the underlying objective. A statement that an adhesive bond is stronger than the stone may be highly favorable in commercial fabrication while simultaneously identifying a potential conservation risk when the substrate is weathered historic marble.

Conversely, conservation terminology can also oversimplify the problem. Describing a material as “reversible” may create unwarranted confidence if the finished treatment cannot realistically be removed without damaging the object. Appelbaum argued that reversibility properly describes a treatment process rather than an inherent property of a material and emphasized that treatments exist across degrees of reversibility. Solubility, therefore, should not be confused automatically with safe removal. A polymer may remain soluble while being inaccessible within a deep fracture; solvent exposure necessary for its removal may itself create risks; and a treatment may penetrate fragile stone sufficiently that complete recovery of the pre-treatment condition is impossible (Appelbaum, 1987).

Current American Institute for Conservation guidance reflects this broader approach. Rather than establishing absolute reversibility as the sole criterion, the AIC directs practitioners to evaluate the suitability of a proposed treatment and to balance the advantages of selected materials and methods against their potential adverse effects on future examination, investigation, treatment, and function. This formulation is particularly useful for structural stone conservation because some interventions—drilling, removal of deteriorated material, consolidation, loss compensation, and the use of thermosetting adhesives among them—cannot meaningfully return the object to an untouched state. The ethical question becomes one of necessity, proportionality, foreseeable consequence, and preservation of future options (American Institute for Conservation, n.d.).

1.3. Repairing the Monument Rather Than Merely Bonding the Joint

A central premise of this paper is that adhesive selection should begin only after the function of the repair has been defined. A detached marble fragment, a transverse fracture through a thin tablet, and the horizontal interface between a monument die and base may

all be described colloquially as pieces of stone that need to be “glued,” yet the forces acting at those interfaces differ substantially.

A thin tablet fractured across its width may require the adhesive to transmit bending, shear, and tensile stresses so that the repaired tablet again behaves approximately as a continuous element. Close-fitting fracture surfaces may permit a very thin adhesive layer, and substantial mechanical interlock may exist because of the irregularity of the break. Under those conditions, the adhesive performs a genuine structural joining function.

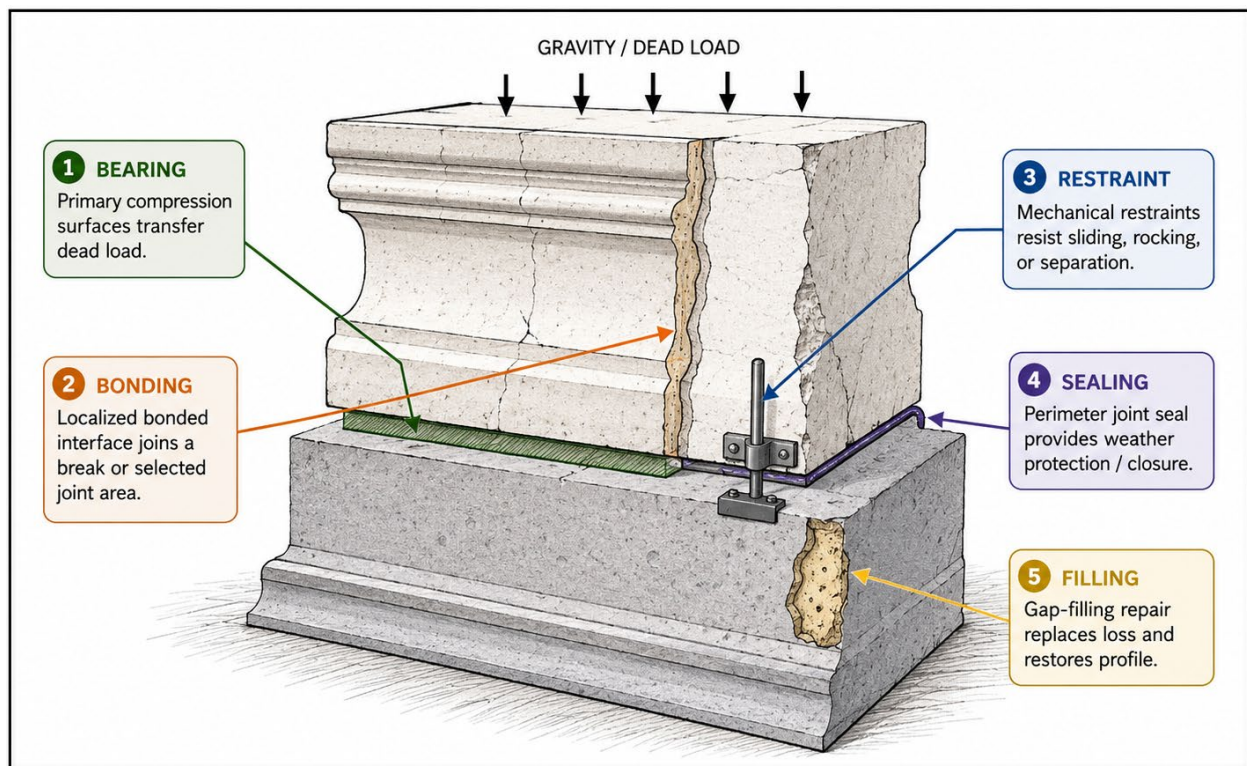
A multi-piece monument presents a different problem. When an upper section bears properly upon a lower section, gravity creates a primarily compressive relationship at the horizontal interface. The structure may require restraint against sliding, rocking, rotation, or accidental displacement, but the adhesive need not necessarily carry the full dead load of the upper stone. Stable bearing, proper alignment, friction, wedges or shims, and the mass and geometry of the monument can perform functions that would otherwise be imposed unnecessarily upon a continuous adhesive bed.

This distinction has direct consequences for material selection. If a permanent structural adhesive is applied continuously across the entire horizontal interface, a large, bonded area is created that may transmit substantial force into the historic stone during future movement. If the same or a similar adhesive is confined to selected locations while the monument is independently supported through stable bearing, the material remains chemically permanent but mechanically occupies a much smaller role in the assembly.

This paper uses the term **limited-bond reassembly** to describe the latter strategy. The concept does not presume that localized adhesive is always safer than full bonding, nor that every monument can be stabilized without mechanical reinforcement. Instead, it establishes an analytical distinction: **the mechanical consequences of a strong adhesive depend partly upon how much of it is used, where it is located, and what loads it is expected to carry.**

These distinctions are illustrated in Figure 1.1, which separates five functions that may coexist within a single monument assembly: bearing, bonding, restraint, sealing, and filling. Treating these functions independently helps prevent structural adhesives from being assigned work that can be performed more appropriately by the monument's geometry, bearing surfaces, or maintainable joint materials.

Figure 1.1: One Monument, Different Structural Functions



Note. A single monument may require different materials or treatment strategies for bearing, bonding, restraint, sealing, and filling. These functions should be distinguished during repair design rather than being treated as a single generic act of “gluing” the monument together.

1.4. Gravestone Guardians’ Current Practice as a Case Study

Gravestone Guardians currently approaches closely fitted tablet fractures differently from the reassembly of larger multi-piece monuments. For tablet breaks in marble considered sufficiently sound to receive structural bonding, Akepox 5010 is generally used as the primary adhesive. The objective is to achieve a thin, closely fitted structural joint without automatically drilling the tablet for internal reinforcement.

For multi-piece monument reassembly, Gravestone Guardians has used Pratley Standard Setting Putty in localized applications in combination with lead wedges and monument setting compound. In that arrangement, the lead assists with alignment and bearing, the monument components remain predominantly compression-loaded by their own weight, localized putty provides additional restraint, and perimeter setting compound addresses the exterior joint. This differs materially from coating an entire interface with structural epoxy and differs again from drilling and installing rigid pins or dowels.

These practices provide useful subjects for analysis because they occupy the disputed middle ground between two established approaches. One emphasizes highly durable structural bonding; the other emphasizes reversibility, compatible weak interfaces, or mechanical reassembly. The purpose of this paper is not to validate existing Gravestone Guardians practice by assumption. It is to subject that practice to the same questions applied to competing methods and determine where its underlying logic is supported, where limitations remain, and where experimental evidence is required.

Three questions are especially important. First, does limiting the bonded area of a high-strength adhesive meaningfully reduce the risk that future failure will remove historic marble? Second, can primary dead loads be carried through stable bearing while adhesive is reserved for restraint, thereby separating structural functions that are often combined in a single material? Third, how does such an intervention compare—not only in immediate strength but in destructiveness and retreatability—with continuous adhesive bonding or drilled mechanical reinforcement?

These questions cannot be answered by product reputation alone.

1.5. The Central Research Problem

The central research problem addressed by this paper can be stated as follows:

How should structural adhesives and associated setting materials be selected and configured so that a repaired historic marble monument possesses adequate structural stability while minimizing the probability and consequence of future damage to original stone?

A related working hypothesis guides the discussion:

A relatively strong and permanent adhesive may be compatible with conservation objectives when its use is structurally justified, its bonded area and role are deliberately limited, primary bearing is provided independently where possible, the stone is sufficiently sound to receive the treatment, and the repair is designed around a minimally destructive failure hierarchy.

This is deliberately framed as a hypothesis rather than a conclusion. High-strength thermosetting polymers remain capable of producing highly destructive failures. Limited adhesive areas may create localized stress concentrations if placed improperly. Lead wedges can be misused. Setting compounds can trap moisture or deteriorate. Mechanical restraint may be insufficient for certain monument geometries. A repair philosophy is only useful if its limitations are examined as seriously as its advantages.

1.6. Scope of the Paper

The primary focus of this study is historic marble cemetery monuments and grave markers assembled from discrete stone components or repaired after fracture. Other calcareous stones are discussed where the literature is relevant, but conclusions derived from marble should not automatically be transferred to limestone, sandstone, slate, granite, cast stone, concrete, terra cotta, or other substrates.

Although marble remains the principal substrate examined in this paper, several system-level principles discussed here may also be relevant to multi-piece granite monuments. These include the separation of bearing from bonding, limitation of permanent bonded area, use of localized structural restraint, treatment of perimeter joints as maintainable elements, selection of mechanical reinforcement according to structural demand, and evaluation of failure hierarchy and retreatability. Granite differs substantially from marble in mineralogy, porosity, weathering behavior, and mechanical properties; consequently, material-specific conclusions derived from marble should not be transferred quantitatively to granite without separate evaluation. Granite is therefore treated as a secondary comparative substrate rather than as a coequal subject of the present study.

The material families examined include structural epoxies such as Akepox 5010 and Tenax Domo 10; epoxy putties including Pratley Standard Setting Putty; selected polyester stone mastics; conservation epoxies such as HXTAL NYL-1 and related systems; thermoplastic acrylics including Paraloid B-72 and B-48N; intervention-layer systems combining a soluble acrylic barrier with a thermosetting structural adhesive; mineral grouts and mortars; lead and other bearing materials; and monument setting compounds.

The paper concentrates upon mechanical behavior, conservation compatibility, failure consequences, exterior durability, and future retreatment. It does not attempt to establish engineering design loads for monuments of every configuration, nor does it provide a universal installation specification. Where a monument requires formal structural engineering, complex anchoring, substantial reconstruction, or public-safety certification, the material-selection framework presented here should support—not replace—appropriate professional evaluation.

1.7. Evidence and the Limits of Existing Research

The available evidence is uneven. Structural adhesives are extensively tested by manufacturers, but test methods are generally designed to characterize product performance under standardized conditions rather than conservation performance on aged cemetery marble. Conservation researchers have conducted valuable marble-to-marble shear, tensile, and fracture-toughness studies, but the number of adhesive systems

and marble types examined is limited. Laboratory specimens are frequently prepared from comparatively sound stone, while historic cemetery marble may possess pre-existing intergranular deterioration, surface friability, salts, moisture, biological contamination, and undocumented previous treatments.

Podany and colleagues demonstrated that conventional structural adhesives and Paraloid B-72 systems could be compared meaningfully using modified tensile and shear tests, while Jorjani and colleagues extended the discussion toward interfacial fracture toughness and bond-line width. Their results establish a useful scientific foundation while simultaneously demonstrating the need for caution in extrapolation. A joint formed between prepared laboratory coupons is not mechanically identical to an irregular fracture through weathered nineteenth-century marble, and a museum sculpture is not exposed to the environmental cycling of a New England cemetery (Jorjani et al., 2008; Podany et al., 2001).

Accordingly, this paper distinguishes where possible between established evidence, manufacturer-reported properties, accepted or documented conservation practice, monument-industry practice, field observation, and hypotheses requiring further experimental validation. Later chapters propose a testing program specifically intended to address several of the gaps that become apparent through this review.

The resulting approach is intentionally broader than a comparison of adhesive products. A product can perform exactly as designed and still be inappropriate for a particular monument. The decisive question is how that product behaves as one component of the repaired historic assembly.

2. Moving Beyond “The Adhesive Must Be Weaker Than the Stone”

2.1. The Conservation Logic Behind a Weaker Repair

Few conservation principles are as intuitively persuasive as the idea that a repair material should fail before the original object. Traditional lime mortar provides a familiar architectural analogy. In many historic masonry systems, the mortar joint is intentionally more accommodating and readily replaceable than the masonry units it separates. When movement or weathering occurs, deterioration of the joint can often be repaired without sacrificing significant portions of the historic brick or stone. A very strong, rigid mortar placed between weaker historic units can invert that relationship and contribute to cracking, edge loss, or spalling of the masonry.

Applied to adhesive repair, the corresponding principle is straightforward: if a broken piece of historic marble is bonded together, the adhesive joint should ideally release before a future overload creates a new fracture in the historic stone.

As a conservation objective, this is difficult to dispute. Original material should not be made sacrificial to a modern repair. Problems arise when the objective is converted into an apparently simple material specification—that the tensile strength of the adhesive must be lower than the tensile strength of the marble.

Neither half of that comparison is as stable as the rule implies.

Historic marble does not possess one universal tensile strength. Mechanical properties vary with quarry source, mineralogy, grain size, fabric, orientation, porosity, microcracking, environmental deterioration, moisture, specimen geometry, and test method. Weathering can progressively reduce cohesion at grain boundaries, and a monument may contain zones of markedly different integrity within only a few centimeters. A sound interior fracture surface may possess considerably greater strength than an exposed sugaring face, while weathering adjacent to a previous repair may create yet another mechanical condition.

An adhesive likewise cannot be reduced to a single number taken from a technical data sheet. Tensile strength may describe the cured polymer under a prescribed test method, the tensile strength of a standardized bonded specimen, or a manufacturer-defined adhesion test. Values produced by different methods are not necessarily directly comparable. More importantly, the force required to break a completed stone joint depends on the adhesive-substrate interface and joint geometry as well as the bulk strength of the polymer.

The result is an important distinction: **the conservation objective is not necessarily a weak adhesive. It is a repair system whose eventual failure does not needlessly sacrifice historic stone.**

Those ideas overlap, but they are not identical.

2.2. Strength Is a Property; Compatibility Is a Relationship

The frequent focus on tensile strength tends to imply that an adhesive can be ranked on a single scale from “safe” to “too strong.” In practice, compatibility is relational. The behavior of the repair depends upon how the cured material interacts with the specific stone and the specific geometry of the joint.

Consider two adhesives. Adhesive A has relatively high ultimate tensile strength but a comparatively moderate elastic modulus. Adhesive B has lower tensile strength but is substantially stiffer. If both are used in otherwise identical joints, Adhesive B may resist deformation more strongly and transfer localized strain into the neighboring marble at lower displacement, even though the polymer itself fails at a lower ultimate stress. Which adhesive is more compatible cannot be answered from tensile strength alone.

The same complication arises with fracture toughness. Tensile strength concerns the stress associated with failure under a particular loading configuration. Fracture toughness addresses resistance to the initiation and propagation of cracks. In a bonded stone assembly containing irregular surfaces, microscopic defects, variable bond-line thickness, pores, and sharp geometric discontinuities, crack initiation and propagation may be more relevant to real failure than the nominal tensile strength of a bulk adhesive sample.

Jorjani and colleagues recognized this distinction in their evaluation of adhesives for marble repair. Rather than relying exclusively upon conventional tensile strength, the study examined **interfacial fracture toughness** and bond-line width for multiple thermoplastic and thermosetting systems, including Paraloid B-72, B-48N, HXTAL NYL-1, Epotek 301-2, Akepox 2000, and polyester mastic. Their work found several thermoplastic systems potentially viable for structural marble repair and demonstrated that meaningful differences among adhesives cannot be captured by a simple strong-versus-weak classification (Jorjani et al., 2008).

The practical consequence is not that strength becomes unimportant. An adhesive that cannot sustain the expected service loads is unsuitable regardless of its favorable conservation properties. Rather, strength should be treated as a threshold requirement. Once adequate capacity is established, other properties determine whether additional strength is beneficial, neutral, or potentially harmful.

This distinction separates conservation engineering from a maximum-performance approach. The objective is **sufficient capacity with acceptable consequences**, not the highest capacity achievable.

2.3. Stiffness and the Transfer of Stress

Elastic modulus deserves particular attention because it describes a mechanical characteristic often obscured by discussion of bond strength. In simplified terms, modulus indicates how much a material resists elastic deformation when loaded. A high-modulus material changes relatively little in shape under a given stress; a lower-modulus material deforms more readily.

A structural joint couples two materials that may possess very different stiffnesses and very different responses to environmental change. Fresh marble is itself relatively stiff, but historic weathering can create a graded system in which surface and near-surface zones are substantially weaker or more microcracked than sound stone deeper within the monument. A cured polymer occupying a fracture may consequently behave as a comparatively intact, coherent inclusion surrounded by deteriorated mineral fabric.

This does not mean that every stiff adhesive will damage marble. Stress transfer depends upon joint shape, thickness, constraint, load direction, and the properties of the adjacent stone. The concern is instead that differences in deformation can concentrate stress near the termination of the bond or along weak portions of the substrate. Where a rigid adhesive layer spans a large area, environmental or mechanical movement that cannot be accommodated by the polymer may be transferred to neighboring stone.

The thermal behavior of marble further complicates this relationship. Calcite grains respond anisotropically to changes in temperature, and differently oriented grains therefore expand and contract in incompatible directions. Repeated cycling can produce intergranular microcracking even without the presence of a repair. An adhesive introduced into that system does not share the same crystalline structure or thermal response. The bonded assembly therefore contains materials that expand, contract, deform, absorb moisture, and age differently (Siegesmund et al., 2000).

The importance of stiffness becomes particularly apparent when comparing thick and thin adhesive masses. A very thin, well-fitted bond line behaves differently from a large volume of filled epoxy occupying a broad void. The latter introduces more polymer, changes the geometry of the interface, and may behave much more like a discrete structural insert. For this reason, a material suitable for a thin fracture bond should not automatically be assumed equally suitable as a thick gap filler, even when the manufacturer permits both uses.

This is one reason the paper treats structural epoxies and epoxy putties separately. The chemical family may be similar, but the geometry in which the material is ordinarily employed can be substantially different.

2.4. Bond-Line Thickness, Surface Area, and Joint Geometry

The mechanics of an adhesive repair are inseparable from the dimensions of the joint. Conservation literature has long recognized bond-line thickness as an important variable, and experimental marble studies have attempted to measure and control it for precisely this reason. Jorjani and colleagues compared measured bond widths across several adhesive systems and related these observations to earlier conservation recommendations concerning suitable joint dimensions (Jorjani et al., 2008).

A closely fitting fracture typically permits a thin adhesive layer. The irregularity of the stone surfaces may also provide a degree of mechanical interlock and substantial true surface area. If the fracture is well aligned, adhesive is largely confined to the volume previously occupied by the break itself. Wide gaps, missing material, uneven bedding surfaces, or intentionally thick putty pads create a different mechanical condition. The repair material becomes more volumetrically significant and may participate in bearing or shape correction in addition to adhesion.

Bonded surface area is equally consequential. The total force required to separate a joint is related not merely to the nominal strength of the adhesive but to the area over which that adhesive develops stress. A high-strength resin covering a few small, deliberately selected locations cannot ordinarily transfer the same total tensile or shear force as the same resin forming an effective bond across an entire broad interface, assuming comparable local stresses and sound adhesion.

This observation provides the mechanical basis for considering limited-bond reassembly as distinct from continuous bonding.

Suppose an upper monument section rests upon a lower base through stable bearing surfaces. If nearly the entire interface is coated with structural epoxy, subsequent rocking, overturning, or frost-related movement may mobilize a large bonded area before separation occurs. The adhesive layer can thereby transfer substantial forces into the marble. If, instead, the upper component is independently and adequately supported while structural adhesive occupies only several selected areas, the maximum force transferred through adhesive is constrained in part by the reduced effective bond area.

This does not automatically make the second arrangement safer. Poorly located adhesive pads can create concentrated loads, particularly near thin edges or deteriorated regions.

Excessively small bonded areas may provide inadequate restraint. Thick putty masses may introduce their own stiffness and moisture-related concerns. The relevant point is that **bond area is a design variable** and should be evaluated deliberately rather than treated as an incidental result of application technique.

The same reasoning applies to adhesive placed in drilled pin holes. Pinning may use relatively little adhesive by volume, but a rigid pin changes the load path by transferring force through concentrated regions of stone surrounding the drilled holes. The comparison between pinning and adhesive-only reassembly therefore cannot be reduced to how much epoxy each method consumes. Geometry determines where the forces go.

2.5. Load Direction Matters

Adhesives do not experience a single universal type of stress in service. A repaired monument can subject a joint to compression, tension, shear, bending, peel, torsion, or combinations of these. Different joint configurations respond differently to each.

Horizontal monument interfaces commonly carry substantial dead load in compression. If bearing is adequate, compression can pass directly through the stone and associated bearing materials without requiring adhesive to suspend the upper component. Adhesive in such a joint may principally resist lateral shear, rocking, or uplift associated with accidental disturbance.

A transverse break in a vertical tablet is mechanically different. Wind, handling, ground movement, or small misalignments may create bending across the repaired section. One side of the joint can experience tension while the opposite side is compressed. The adhesive is consequently more integral to the ability of the tablet to behave as a continuous element.

Edge fragments and projections create yet another condition because peel forces can become significant. Adhesive joints are often less efficient when load is concentrated progressively along an edge than when stress is distributed uniformly across the bonded area. A product that performs exceptionally in a standardized lap-shear test may therefore provide limited information about its behavior in a thin projecting marble fragment subjected to bending and peel.

Podany and colleagues recognized this distinction when adapting mechanical tests for marble sculpture. Their work included both shear and tensile evaluations because the loading of reassembled sculpture could not be represented adequately by shear testing alone (Podany et al., 2001).

The treatment decision should therefore begin with the probable load path. Only after identifying what the joint must resist is it meaningful to ask how much adhesive capacity is required.

2.6. What Marble Adhesive Tests Reveal About the “Weak Joint” Principle

The experimental work of Podany and colleagues provides one of the clearest demonstrations of why the requirement for a deliberately weaker adhesive is difficult to implement in practice. Marble specimens were bonded using conventional epoxy, polyester adhesive, Paraloid B-72 formulations, and systems incorporating B-72 as a barrier beneath structural adhesive. In both tensile and shear testing, the conventional epoxy- and polyester-bonded samples generally failed in the marble rather than within the adhesive bond. This result is consistent with the conservation concern surrounding very strong structural adhesives: the bond can remain intact while the substrate becomes the sacrificial component (Podany et al., 2001).

The more revealing result, however, involved B-72. With very limited exceptions attributed by the researchers to anomalous specimens or preparation variables, the tensile specimens employing B-72 also failed within the marble. In other words, selecting an acrylic resin valued for conservation reversibility did not guarantee that the adhesive interface would release before the stone fractured (Podany et al., 2001).

This should not be interpreted as an argument against B-72. Quite the opposite: the study demonstrated that a comparatively retreatable acrylic could provide substantial structural capacity and could function as an intervention layer beneath less reversible adhesives. The result instead exposes a weakness in the simplistic formulation of the sacrificial-joint rule. If even a conservation acrylic can develop sufficient adhesion for the marble specimen to fail first, then product category alone cannot create the desired failure hierarchy.

Jorjani and colleagues reached a complementary conclusion through fracture-toughness testing. Across the systems examined, the predominant failure pattern demonstrated that the adhesives as a group possessed sufficient capacity to join marble. Several thermoplastic formulations therefore remained mechanically credible alternatives to thermosetting adhesives under the conditions tested (Jorjani et al., 2008).

These studies are valuable, but their limitations are equally important. Laboratory marble coupons prepared from relatively sound material do not replicate every condition found in historic cemeteries. A heavily weathered tablet with granular disintegration may fail at substantially lower stresses than laboratory stone. Adhesive may penetrate into a friable surface zone, creating a locally consolidated region immediately adjacent to unconsolidated marble. Environmental cycling may alter both the polymer and the stone

over decades. The fact that B-72 or epoxy caused cohesive marble failure in one controlled test therefore does not establish the precise force or failure mode that will occur in an aged monument.

What the studies establish more convincingly is methodological: **failure location must be measured rather than assumed.**

2.7. Reconsidering Reversibility

The same analytical care should be applied to reversibility. Conservation discussions often contrast permanent epoxy with reversible acrylic resin as though the difference alone determines treatment quality. Chemically, the distinction is important. A cross-linked thermosetting epoxy cannot ordinarily be redissolved and returned to its uncured state, while thermoplastic acrylics such as B-72 can retain solubility in appropriate solvents. From the standpoint of treatment practice, however, the relevant question is whether the completed intervention can be undone without unacceptable risk to the monument.

Appelbaum's distinction between material solubility and treatment reversibility is especially useful here. A soluble adhesive buried within a deep, closed stone joint may be difficult to expose to sufficient solvent without extended saturation or mechanical separation. Conversely, a permanent adhesive confined to several documented, accessible pads may in some circumstances permit future dismantling through careful mechanical removal while sacrificing only the treatment material and limited associated surfaces. Neither situation can be classified responsibly from chemistry alone (Appelbaum, 1987).

Attempts to reverse structural epoxy can themselves create risk. Podany and colleagues noted earlier Getty investigations in which solvent exposure caused several epoxy and polyester formulations to swell substantially. If a swollen adhesive is confined within a joint or drilled hole, expansion can exert pressure on surrounding marble and potentially damage fragile surfaces. This is an instructive reminder that “removing” a permanent adhesive chemically is not necessarily safer than leaving it in place or removing it mechanically (Podany et al., 2001).

The more useful concept for exterior monument repair is therefore **retreatability**. Retreatability accepts that the initial treatment may leave some irreversible evidence while asking whether future practitioners retain practical options. Can the monument be dismantled? Can a failed joint be accessed? Can degraded perimeter material be replaced independently? Can structural adhesive be isolated from large areas of original surface? Is the location of the adhesive documented? Can one component be retreated without dismantling or damaging the remainder?

This approach is consistent with modern conservation ethics because it evaluates the treatment in relation to future intervention rather than treating reversibility as a binary material designation (American Institute for Conservation, n.d.).

2.8. From Material Sacrificiality to Failure Hierarchy

The traditional preference for a weak repair should therefore be retained as an ethical objective but reformulated mechanically. The essential conservation goal is not that every repair material possess lower laboratory strength than every portion of historic stone. The goal is to arrange the repaired assembly so that foreseeable deterioration or overload produces the least damaging practical consequence. This paper defines that arrangement as a failure hierarchy.

At its simplest, failure hierarchy asks what is expected to give way first, what happens next, and how much historic material is lost in the process. A desirable hierarchy may place replaceable perimeter material, localized restraint, or an accessible adhesive interface ahead of significant fracture of original stone. An undesirable hierarchy may leave a large area of modern structural adhesive completely intact while a new crack propagates deeply through the monument adjacent to the repair.

The concept also accommodates cases in which no truly weak material is available. If every adhesive capable of providing the required structural capacity is strong enough to damage deteriorated marble, risk may instead be reduced through geometry. Bonded area can be limited. Adhesive can be placed away from fragile edges. Dead load can be transferred through stable bearing rather than suspended through resin. A thermoplastic barrier may be introduced where appropriate. Mechanical reinforcement can be avoided when it is unnecessary or included when structural demand requires it. Accessible setting material can be designed for periodic replacement.

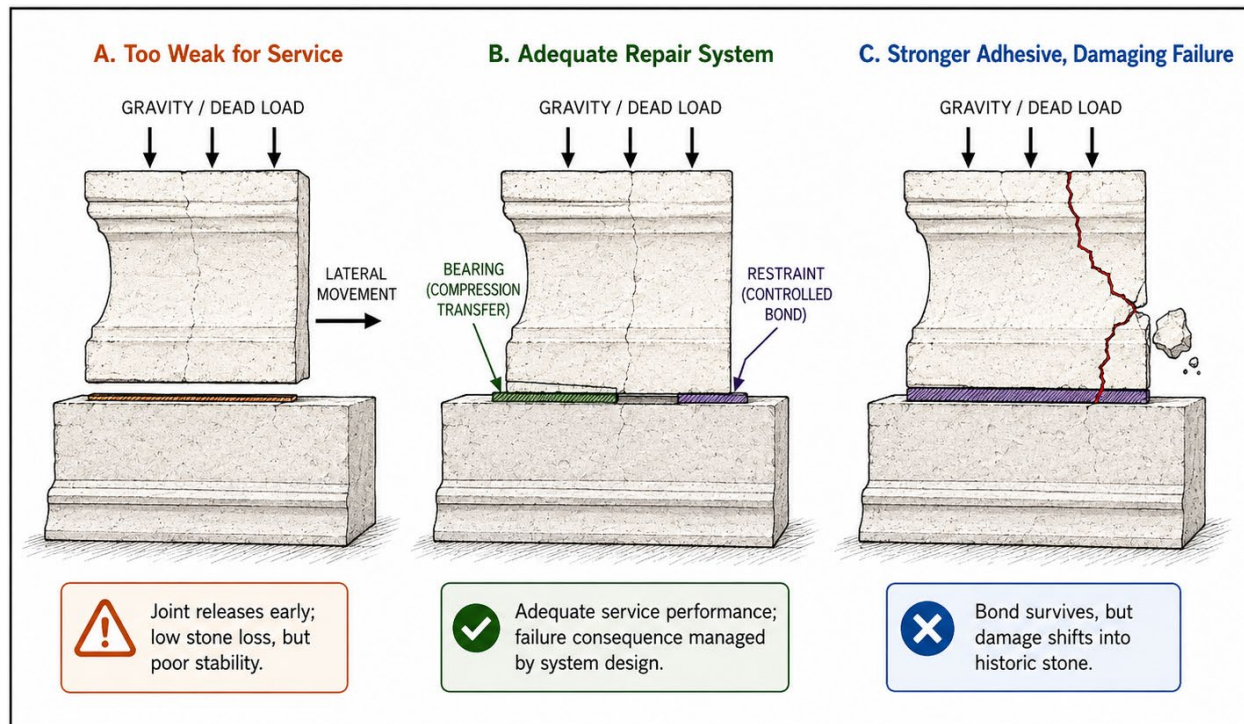
In this broader framework, sacrificiality becomes a property of the **repair system** rather than exclusively a property of the adhesive.

This distinction is particularly important for Gravestone Guardians' use of localized Pratley Putty with lead wedges and monument setting compound. The cured putty may itself be a strong and permanent material. If the conservation argument depends upon proving that Pratley is inherently weaker than historic marble, that argument may be difficult to establish and may ultimately be unnecessary. The more relevant question is whether the arrangement constrains the structural role and effective bonded area of the putty sufficiently that the overall system presents a less invasive and less destructive risk than continuous adhesive bonding or drilled reinforcement.

That proposition requires testing. It cannot be established through field experience alone. Yet it provides a mechanically coherent hypothesis that can be evaluated.

Figure 2.1 illustrates why a simple hierarchy in which the adhesive is expected to fail before the stone cannot, by itself, define a conservation-compatible repair. Adequate treatment must consider both the load required to produce failure and the consequences of that failure for the historic stone and the stability of the assembly.

Figure 2.1: Why “Adhesive Weaker Than Stone” Is an Incomplete Model



Note. Relative adhesion strength alone does not determine conservation suitability. A joint that is too weak may release under normal service and create instability, whereas an overly strong or overly rigid bond may direct damage into historic stone. The preferred repair provides adequate service performance while minimizing damaging failure consequences.

2.9. Adequate Strength Versus Excess Capacity

Structural safety imposes an important boundary upon any discussion of sacrificial repair. A joint designed to release so readily that normal service loads, routine handling, wind, or minor accidental contact can destabilize a monument is not conservative. An unstable monument threatens itself, nearby monuments, cemetery workers, visitors, and future treatments. Under-strength repair can therefore be as incompatible with preservation as excessive rigidity.

The design objective should be adequate reserve capacity above reasonably anticipated service demands without pursuing unnecessary bond strength merely because stronger products are available. This resembles a broader engineering distinction between required performance and maximum available performance. The treatment should provide enough capacity to perform its intended function reliably, while recognizing that capacity beyond the level required may provide little conservation benefit if its principal consequence is to transfer greater loads into original stone.

Determining that threshold is not always straightforward. Cemetery monuments are exposed to uncertain events: frost movement, settlement, falling branches, vandalism, accidental impact, severe weather, inappropriate handling, and future maintenance. A repair designed only for the static weight of a component would be inadequate. Podany and colleagues made a similar observation in calculating loads on reassembled sculpture: static forces may be modest, while dynamic loads from handling or accidental actions can greatly exceed them (Podany et al., 2001).

Conservation restraint therefore does not mean designing a fragile joint. It means resisting the temptation to treat the highest possible adhesive capacity as inherently preferable.

2.10. A More Useful Conservation Principle

The statement that “the adhesive should be weaker than the stone” can now be replaced with a more precise working principle for this paper:

A structural repair should possess sufficient capacity for foreseeable service while being configured so that excessive loading, environmental deterioration, or future retreatment is unlikely to cause disproportionate loss of original historic stone.

This formulation retains the preservation intent behind traditional sacrificial repair but expands the variables considered. Adhesive strength remains relevant, but it is evaluated alongside stiffness, fracture behavior, bond area, bond-line thickness, geometry, bearing, stone condition, environmental response, permanence, and retreatability.

It also avoids presenting conservation as a choice between weak traditional materials and strong modern ones. Mineral mortars, thermoplastic acrylics, epoxies, putties, lead wedges, pins, and monument setting compounds perform different functions. Their suitability depends upon what the monument actually requires.

The implications are significant for the chapters that follow. AKEPOX 5010 cannot be evaluated merely by asking whether its cured tensile strength exceeds that of weathered marble. Pratley Standard Setting Putty cannot be dismissed or validated solely from its reputation as a high-strength epoxy putty. Tenax Domo 10 cannot be judged solely by

commercial claims of substrate-breaking adhesion. Paraloid B-72 cannot be assumed to create a sacrificial joint simply because it remains soluble. Mineral grout cannot be selected merely because its chemistry resembles masonry more closely than a polymer does.

Each material must instead be placed within a defined structural role and examined as part of the complete monument assembly.

That shift—from **“How strong is the glue?”** to **“How does the repaired monument carry load, move, age, fail, and permit future treatment?”**—provides the analytical foundation for the remainder of this study.

3. Failure Hierarchy and System-Level Sacrificiality

3.1. From a Sacrificial Material to a Sacrificial System

The preceding chapter argued that the familiar conservation preference for an adhesive weaker than the historic stone expresses a valid objective but provides an incomplete method for achieving it. The underlying concern is not weakness for its own sake. It is the preservation of original material when a repaired assembly eventually deteriorates, moves, is overloaded, or requires another intervention. Once the problem is expressed in those terms, attention shifts from a single material property toward the behavior of the entire repaired monument.

This paper uses the term **failure hierarchy** to describe the anticipated sequence and location of damage when a repair system is subjected to forces exceeding its normal capacity. A failure hierarchy may involve the adhesive interface, the adhesive itself, a setting compound, a bearing material, a mechanical connection, or the historic stone. The objective of conservation-oriented design is not to guarantee that original material can never fail; no treatment can provide such certainty. Rather, the repair should avoid unnecessarily arranging the system so that irreplaceable historic material becomes the most likely or most consequential point of failure.

The concept becomes more useful when paired with what this paper terms **system-level sacrificiality**. Traditional sacrificiality is commonly associated with a single material selected because it is softer, weaker, more permeable, or more readily replaced than the historic substrate. Lime mortar joints between historic masonry units provide the familiar example. System-level sacrificiality expands the concept beyond individual material strength. A repair may instead be made comparatively conservative through the combined effects of limited bonded area, accessible joints, replaceable setting materials, appropriate bearing, reduced drilling, localized restraint, and documentation that allows later practitioners to understand where permanent interventions were made.

Under this framework, a strong material can exist within a conservation-oriented assembly without necessarily becoming the governing structural element. Its compatibility depends upon the role assigned to it, the area over which it acts, the condition of the substrate receiving it, and the consequences if the repaired system is later overloaded.

This distinction is important because permanent intervention cannot always be avoided in structural conservation. Drilling a hole for a pin permanently removes original stone. Consolidation may alter pore structure and mechanical behavior. Loss compensation introduces new material that cannot necessarily be removed without affecting neighboring

surfaces. Epoxy creates a cross-linked polymer that cannot simply be redissolved. Even dismantling and resetting can alter original interfaces. The meaningful question is therefore not whether a treatment leaves absolutely no permanent evidence, but whether the amount and consequence of that permanent intervention are proportionate to the structural problem being solved.

Modern conservation ethics are compatible with this more contextual approach. The American Institute for Conservation emphasizes selection of appropriate materials and methods while balancing treatment benefits against potential adverse effects on future examination, treatment, scientific investigation, and function. Reversibility remains important, but it operates within a broader obligation to preserve future options and minimize unnecessary change. The Getty's treatment of heavily restored ancient stone sculpture similarly demonstrates that structural stability may be pursued by reducing new penetrations, minimizing adhesives, and designing the assembly so future separation remains possible rather than assuming that maximum permanent joining represents the safest treatment (Daehner & Shelley, 2018).

Failure hierarchy therefore provides a bridge between conservation ethics and structural mechanics. It allows the practitioner to ask, before selecting a particular product, not merely whether the adhesive is strong enough, but how the complete assembly is expected to respond when conditions no longer remain ideal.

3.2. Every Repair Creates a New Structural System

A repaired monument is not simply the original monument restored to its previous state. Once adhesive, pins, wedges, grout, mortar, setting compound, replacement stone, or other materials are introduced, the resulting assembly possesses a new distribution of stiffness, strength, contact, and movement. Even when the repair is visually unobtrusive, mechanically it may differ considerably from the original construction.

This point is especially significant in historic cemetery monuments because many were originally assembled through relatively simple means. Large stone components were often stacked through gravity and careful bearing, with setting materials, lead, metal cramps, pins, dowels, or other details added according to the monument type and construction tradition. The performance of the monument depended not upon one continuous homogeneous material but upon the interaction of mass, geometry, friction, bearing, foundations, and selected connections.

Repair can unintentionally simplify that original system into a single modern bond. A deteriorated horizontal joint between two marble components, for example, may originally have permitted small amounts of movement while transferring vertical load primarily

through stone bearing. Filling the interface continuously with rigid structural epoxy creates a different condition. The upper section is no longer merely resting upon the lower one; it has become adhesively coupled across a broad surface. Movement that once might have produced minor sliding, opening, or deterioration of a replaceable setting material may instead be transferred into the marble.

The fact that the new system is stronger under one loading condition does not establish that it is more durable or more conservative under all conditions. Strengthening one element can relocate failure into another. This is a fundamental characteristic of structural systems: modifying the resistance or stiffness of one component changes the distribution of forces throughout the assembly.

The same principle applies to pinning. Installing a rigid dowel across a joint may significantly increase resistance to separation, shear, or bending. It also creates localized regions where loads are transferred between the dowel, adhesive surrounding the dowel, and drilled stone. If the surrounding marble is sound and the loads justify reinforcement, this may be an entirely appropriate structural intervention. If the marble is severely weakened or the loads could have been managed through stable bearing and less invasive restraint, the rigid connection may simply relocate future fracture around the pin.

Technical Paper No. 2 examined this problem primarily through the question of pinning versus adhesive repair. The present paper broadens the analysis. Pins, epoxies, putties, acrylics, grout, lead, and setting compounds should not be understood as competing products seeking to perform the same function. They are components that can alter the structural behavior of a monument in very different ways.

3.3. Defining the Intended Failure Hierarchy

It is tempting to describe the ideal repair hierarchy as one in which treatment material always fails before historic stone. In practice, such a requirement is too absolute. Some monument components are so heavy, slender, exposed, or geometrically unstable that premature release of a restraint could create a more serious preservation and safety problem than localized damage associated with a stronger connection. A successful hierarchy must therefore consider both the probability of failure and the consequence of failure.

For a stable, low, multi-piece monument whose components possess generous bearing surfaces, the preferred hierarchy may allow perimeter setting compound to age and require replacement long before localized adhesive restraint or original marble is affected. If unusual lateral movement later occurs, controlled separation at a limited bonded region may be preferable to a new fracture extending through the stone.

For a projecting fragment on a sculptural monument, the hierarchy may need to be different. A joint that releases under modest environmental or accidental load could permit the fragment to fall and shatter. Greater connection strength may therefore be justified even though the consequence of a severe future overload could include cohesive failure of the marble.

The design problem is not to make every repair intentionally weak. It is to avoid strength or rigidity that does not serve a defined structural purpose.

This requires identifying the normal service condition first. The monument should remain safe and stable under its own weight, expected environmental exposure, modest handling associated with maintenance, and reasonably foreseeable incidental forces. Once sufficient capacity exists for those conditions, additional strength should be evaluated according to what it changes in the failure sequence. If doubling the effective adhesive capacity does not materially improve the monument's required stability but substantially increases the amount of historic stone likely to be mobilized during an extreme event, the added capacity may offer little conservation advantage.

Failure hierarchy is therefore an exercise in proportionality. It asks how much intervention is required, where that intervention should act, and which component should be allowed to surrender when forces exceed what the conservation treatment was reasonably designed to withstand.

3.4. Separation of Structural Functions

One of the most useful consequences of thinking in terms of failure hierarchy is the ability to separate functions that are often assigned to a single material. In monument repair, the functions of **bearing, alignment, restraint, bonding, gap filling, sealing, and weather protection** are frequently conflated. A practitioner may apply a large quantity of adhesive because the product is being asked simultaneously to support weight, fill irregular space, establish alignment, resist movement, and close the exterior joint.

A more controlled repair attempts to determine which function truly requires adhesive.

Bearing is the transfer of compressive load between surfaces. In a multi-piece monument, the mass of the upper stone should ordinarily pass downward through stable support rather than being suspended within a polymer adhesive. If irregularities prevent proper bearing, those irregularities should be understood as a support problem rather than automatically solved by creating a thick adhesive mass.

Alignment is likewise distinct. Lead wedges and other suitable shimming materials can establish level, plumb, or uniform bearing at selected locations. Their purpose is not

principally to glue the monument together but to control contact geometry and distribute load.

Restraint addresses movement such as sliding, rocking, rotation, or separation. Adhesive may perform this role without necessarily covering the entire interface. Mechanical reinforcement may also provide restraint where the forces and geometry warrant it.

Gap filling addresses missing volume, while sealing or joint closure addresses water entry and exposure at the perimeter. Neither necessarily requires the same material that carries structural load.

Keeping these functions conceptually separate makes over-treatment easier to identify. A strong adhesive may be entirely appropriate for restraint but unnecessarily invasive as a full-area bedding compound. A lime-based material may be suitable for joint closure but inadequate for a tensile fracture. Lead may be excellent for adjusting bearing but inappropriate as the sole safeguard against overturning. A pin may provide necessary reinforcement but should not be expected to correct an unstable foundation.

This functional separation is central to the limited-bond model examined later in this paper.

3.5. Limited-Bond Reassembly as a Failure-Control Strategy

Limited-bond reassembly refers to a configuration in which adhesive is deliberately prevented from becoming the sole or dominant structural mechanism where monument geometry permits other means of support. The stone is placed into stable bearing; alignment is established independently; adhesive is applied only where restraint is needed; and a perimeter material may then perform the separate role of joint closure or weather protection.

The conservation rationale does not depend on the localized adhesive being intrinsically weak. Instead, it depends upon controlling how much force the adhesive can transfer and where that force enters the stone.

This point requires qualification. Reducing bonded area does not produce a simple proportional reduction in risk. Stress is not necessarily distributed uniformly through an adhesive joint, and small adhesive pads can create high localized stresses if they are poorly positioned. Placing a strong putty close to a thin edge, weakened corner, historic carving, previous fracture, or sugared zone could be considerably more damaging than using a larger but more favorably located bond. The geometry and condition of the receiving stone therefore remain essential.

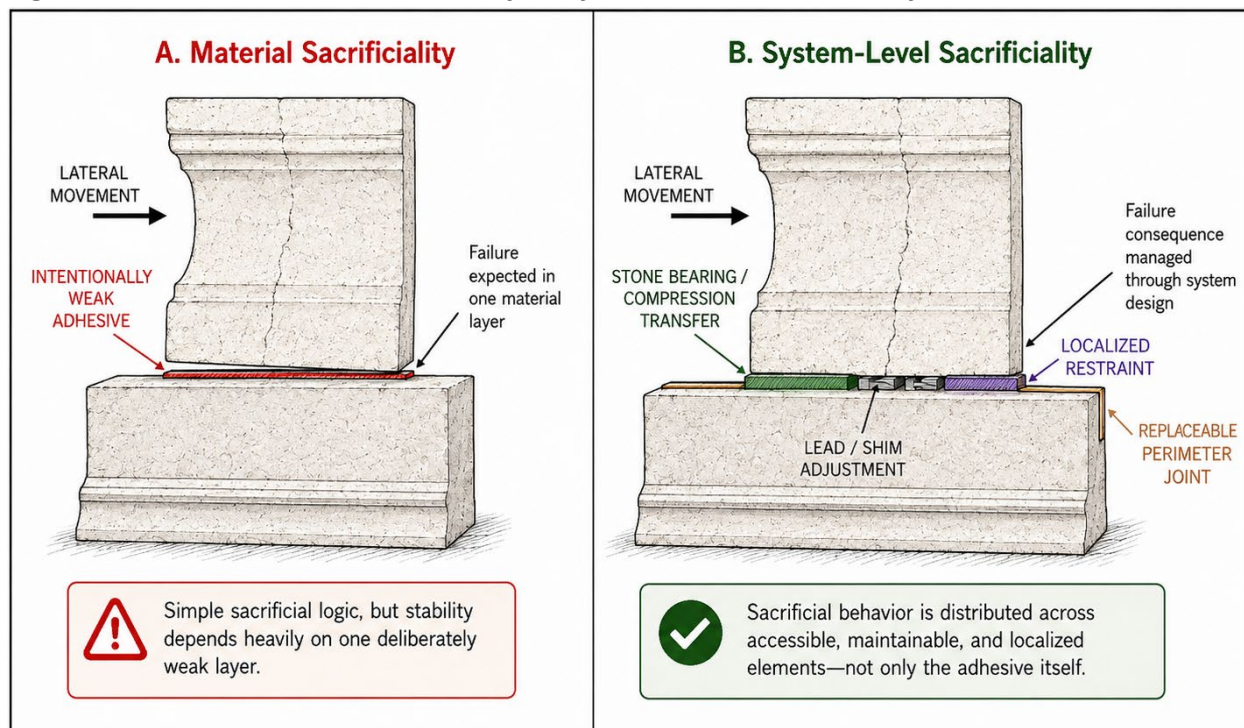
Nevertheless, effective bonded area is one of the variables available to the conservator. A continuous adhesive film extending over nearly the full surface of a die-to-base interface creates a fundamentally different structural connection from several localized areas intended primarily to resist displacement. The first arrangement couples a large proportion of the two surfaces; the second leaves much of the interface mechanically independent except through bearing and friction.

This distinction becomes especially important during future retreatment. A monument connected by localized, documented adhesive pads may offer accessible pathways for separation once perimeter material is removed, although actual retreatability will depend on geometry and adhesive properties. A fully bonded horizontal surface may provide no comparable access. Separation may require cutting, heat, solvents, impact, or destructive mechanical force, any of which can create unacceptable risks.

Limited bonding should therefore be understood neither as a shortcut nor as a formula specifying a particular number or size of adhesive pads. It is a design principle: **use no more permanent adhesive interface than the structural problem requires.**

The distinction between a sacrificial material and a sacrificial repair system is shown in Figure 3.1. Rather than requiring one adhesive to provide the preferred failure mechanism by itself, system-level sacrificiality distributes bearing, restraint, joint protection, and future maintenance among components with different degrees of permanence and replaceability.

Figure 3.1: From Material Sacrificality to System-Level Sacrificality



Note. A repair does not become conservative merely because one adhesive is weaker than the stone. System-level sacrificality seeks adequate service performance while directing maintenance, deterioration, or manageable failure toward accessible, limited, and replaceable components wherever practical.

3.6. The Role of Bearing in Sacrificial Design

Stable bearing is particularly important because it can reduce the number of structural demands placed upon adhesive. A monument component whose weight is properly supported does not need adhesive to prevent it from moving downward. The primary role of the connection shifts toward resistance to lateral displacement, rocking, overturning, or accidental uplift.

This is not a trivial distinction. Compressive loads are generally well suited to stone. Marble has historically been used in columns, bases, blocks, walls, sculpture pedestals, and monuments precisely because sufficiently sound stone can carry substantial compressive load. Historic marble becomes more complicated where contact is concentrated on a few small asperities or deteriorated regions, but the fundamental principle remains: broad, stable bearing is preferable to making adhesive compensate for inadequate support.

National Park Service cemetery guidance illustrates the importance of allowing the physical support system to perform its appropriate function. In guidance for government-issued upright headstones, the NPS specifically cautions against rigid concrete fixing,

noting that soil movement, drainage problems, coffin decay, animals, vandalism, and freeze-thaw can shift markers and that rigidly encasing them can make them more prone to snapping and more difficult to reset. In contrast, a properly ground-supported marker remains comparatively straightforward to realign (National Park Service, n.d.-e).

The example involves ground-supported markers rather than stacked monuments, but the conservation principle is transferable: greater restraint does not automatically produce greater preservation. A connection should be strong enough for the system in which it operates while allowing foreseeable maintenance and environmental movement to occur without unnecessarily converting those movements into stone fracture.

For multi-piece monuments, this means that proper foundation condition, level bearing, contact geometry, and alignment should be addressed before adhesive strategy. A monument resting unstably on three irregular high points cannot be made fundamentally sound merely by filling the remaining space with strong epoxy. The resulting polymer may carry loads it was never intended to carry, while the stone remains poorly supported.

3.7. Wedges and Replaceable Interfaces

Wedges or shims occupy a deceptively important place within system-level sacrificiability because they can alter bearing without requiring removal of original stone. Traditional monument practice has long employed lead for this purpose because it is soft, malleable, conformable, and capable of supporting substantial compressive load while accommodating slight surface irregularity.

Within a conservation-oriented assembly, wedge lead can serve several functions. It may assist in establishing level and plumb, prevent concentrated stone-to-stone contact at isolated high points, create controlled joint spacing, and permit fine adjustment during setting. Because the wedge is discrete and accessible near the perimeter, it may also be more readily altered or replaced than material bonded across the entire interface.

Lead is not without limitations. It undergoes time-dependent deformation under sustained load, can be displaced if improperly located, and should not be treated as a substitute for a sound bearing design. Small wedges supporting excessive loads can create concentrated contact zones. Wedges should therefore assist load distribution rather than reduce a broad bearing surface to a handful of highly loaded points.

The important conservation characteristic is not that lead is universally superior to other bearing materials. It is that **bearing can be deliberately designed as an independent, partially replaceable layer rather than becoming an accidental function of structural adhesive.**

This distinction allows a multi-piece monument to retain a greater degree of mechanical legibility. Future practitioners can identify the interface, remove perimeter materials, observe bearing points, and understand how the monument was set. Such legibility contributes to retreatability even where localized permanent adhesives remain within the assembly.

3.8. Perimeter Joints as Maintenance Elements

Exterior monument joints are exposed to water, biological growth, dirt accumulation, freeze-thaw conditions, and repeated thermal movement. The material visible at the perimeter therefore performs a different function from an adhesive concealed deeper within the interface. Treating the perimeter joint as a maintenance element can contribute significantly to system-level sacrificiality.

A perimeter material should not be assumed to provide the primary structural bond simply because it remains visible and continuous around the monument. Depending upon the product and monument, its more appropriate role may involve exclusion of bulk water, reduction of debris entry, accommodation of small dimensional changes, and protection of the concealed bearing interface.

This has important consequences for retreatment. If the external joint material ages or detaches, it should ideally be possible to renew it without dismantling the monument or disturbing original stone. Conversely, if a rigid structural adhesive is intentionally smeared across the exterior perimeter and tooled to serve simultaneously as both bond and weather joint, maintenance of that interface becomes inseparable from the permanent adhesive intervention.

A layered system can therefore produce a more favorable hierarchy. The exposed material may deteriorate first and be replaced periodically. Bearing materials remain behind it. Localized structural restraint remains further within the interface and may never require intervention unless the monument experiences significant movement. Original stone is thereby protected not by a single deliberately weak product but by several components performing distinct roles.

This is the essence of system-level sacrificiality.

3.9. Permanence Is Not Equivalent to Total Irretrievability

The word *permanent* is often used as though all permanent treatments create the same conservation burden. They do not. A drilled stainless-steel dowel surrounded by cured epoxy is permanent in one manner. A thin epoxy film across a clean fracture is permanent in another. Several small epoxy-putty pads concealed within a horizontal setting joint

constitute a third condition. Their chemistries may all be difficult or impossible to reverse chemically, yet the amount of original material altered, the accessibility of the intervention, and the options available during later repair differ considerably.

This distinction should not be used to minimize the significance of irreversible materials. Once epoxy penetrates a porous stone surface and cures, restoration of that surface to its exact pretreatment condition is unlikely. Once a hole is drilled for a dowel, the removed marble cannot be restored. Conservation documentation should state these realities plainly.

At the same time, practical retreatability depends upon the configuration of the treatment. A permanent intervention occupying two small, documented areas may preserve more future options than a nominally soluble adhesive that has deeply penetrated a friable fracture and cannot be reached effectively with solvent. Earlier adhesive studies have demonstrated that efforts to weaken some epoxies and polyesters with solvent can cause substantial resin swelling; where the adhesive is confined in a joint or hole, that expansion may itself threaten marble (Podany et al., 2001).

The appropriate comparison is therefore not permanent versus reversible in the abstract. It is the degree to which each completed treatment preserves future choices while satisfying present structural requirements.

3.10. Failure Hierarchy as a Treatment-Design Discipline

Failure hierarchy should ultimately function as a discipline imposed before the repair is executed. The practitioner should be able to explain how the monument carries its ordinary loads, which component provides each form of restraint, and where damage is most likely to occur if movement exceeds the design assumptions.

Where that explanation is unclear, the repair may be relying too heavily on a material rather than on a structural concept.

For a closely fitted tablet fracture, the adhesive may legitimately be central to the repaired structural behavior. The failure hierarchy should therefore focus on the condition of the marble adjacent to the joint, bond-line configuration, stiffness, and the likely consequence of future bending or impact.

For a broad horizontal interface between large monument components, the hierarchy should usually begin with foundation and bearing. Adhesive, where necessary, becomes a secondary restraint rather than the default means of supporting weight.

For a projecting sculptural element or a monument whose geometry creates substantial overturning demand, mechanical reinforcement may become appropriate because failure of a deliberately weak connection could itself destroy the object.

No single hierarchy fits all three conditions.

The value of the concept lies precisely in resisting universal prescriptions. Conservation-oriented repair does not mean always choosing the weakest material, always avoiding pins, always minimizing adhesive regardless of consequence, or always reproducing original construction. It means arranging the treatment so that the required stability is achieved with the least unnecessary alteration and with deliberate consideration of how the system will age, fail, and eventually be repaired again.

The chapters that follow place that principle within the mechanics of actual cemetery monuments and the variable physical condition of the marble itself.

4. How Historic Marble Monuments Carry Loads

4.1. Monument Stability Begins Before the Adhesive Joint

Discussions of monument repair frequently begin at the visible break or open joint. Structurally, however, the condition of that joint may be only the final expression of forces originating elsewhere. Foundation settlement, soil movement, inadequate bearing, rotation of a lower component, erosion, frost action, vegetation, previous resetting, or displacement by impact can all alter the loads acting through a monument long before the joint itself separates.

This matters because an adhesive cannot correct a defective load path. If the foundation continues to settle unevenly, bonding the upper sections more strongly may simply force a greater portion of the resulting distortion into the marble. If a base is out of level, rigidly joining the die to the base does not eliminate the eccentric loading; it can make the two components respond as a more rigid unit while the underlying instability continues.

National Park Service cemetery guidance repeatedly identifies shifting soil, flooding, poor drainage, freeze-thaw, animal disturbance, and settlement as causes of monument movement. NPS guidance likewise emphasizes stabilization and proper support rather than attempting to force unstable stones into position (Church, 2021).

Adhesive repair should therefore be approached from the ground upward. The condition of the foundation and lower monument components establishes the geometry through which every subsequent load passes. A sound adhesive joint installed on an unstable support system may be technically successful as an adhesive bond while failing as a conservation treatment.

4.2. Dead Load and Compression

The most constant force acting on a monument is its own weight. This gravitational force, commonly referred to as dead load, acts downward through the mass of each component. In a properly assembled stacked monument, much of that weight is transferred through compression across horizontal interfaces.

Compression is generally advantageous for sound stone because the material is being pressed together rather than pulled apart. The important qualification is that compression must be distributed appropriately. If two surfaces contact only at isolated projections, chips, grains, old mortar remnants, or poorly positioned wedges, the average weight of the upper stone may appear modest while local contact stresses become very high.

This distinction explains why bearing condition matters as much as total monument weight. A large die resting broadly and evenly upon a base distributes its dead load over a substantial area. The same die supported at only a few small points subjects those points to much greater stress. If one of the contact zones lies near a weakened edge or previous fracture, chipping or localized crushing can result even though the stone would easily carry the same total weight under better bearing conditions.

Adhesive can obscure this problem. A thick gap-filling resin placed into a poorly fitting interface may eventually carry some portion of the vertical load. Depending upon the adhesive and geometry, this may or may not be harmful, but it changes the material from restraint to structural bedding. The polymer is now participating directly in support of the monument and may creep, shrink, deform, or redistribute stresses differently from the stone.

For this reason, the question “How much weight can this epoxy support?” is usually less useful than “Why is the epoxy being asked to support the weight at all?”

Where geometry permits broad, stable bearing, the marble and appropriate bearing materials should ordinarily perform that function.

4.3. Center of Mass and Stability

Weight alone does not determine whether a monument is stable. The position of the monument's center of mass relative to its supporting footprint is equally important.

A low, broad monument can be extremely heavy yet difficult to overturn because the line of action of its weight remains comfortably within the base under modest lateral loads. A tall, slender monument can possess less total mass while being substantially more susceptible to rocking or overturning because its center of mass is higher and the available resisting footprint is narrower.

When a lateral force acts upon the monument—through wind, contact, vandalism, maintenance equipment, falling vegetation, or other causes—it creates an overturning moment. The resisting weight of the monument creates an opposing stabilizing moment. As lateral demand increases, contact pressure beneath the monument becomes uneven. One edge carries greater compression while the opposite edge experiences reduced compression. If the overturning demand becomes large enough, part of the interface can lift away from the supporting surface.

This transition is critical to adhesive design. Before uplift occurs, a horizontal joint may be carrying primarily compression and shear. Once one side begins to open, adhesive crossing that region is placed into tension or peel. A full-area structural bond can resist this

opening and thereby increase overturning capacity, but it also transfers tensile force into the stone. A limited-bond system provides less total tensile restraint and therefore may allow separation at a lower extreme load.

Neither condition is automatically correct. The appropriate resistance depends upon the monument's geometry, public-safety exposure, condition, and expected environment. What matters is recognizing that adhesive changes the overturning mechanics by enabling the interface to transmit forces that an unbonded bearing joint cannot.

4.4. Sliding and Shear

A horizontal force insufficient to overturn a monument may instead cause one component to slide relative to another. Resistance to sliding can arise from friction, surface irregularity, mechanical interlock, dowels, pins, adhesive, or combinations of these.

Frictional resistance depends upon the normal compressive force and the characteristics of the contacting surfaces. A heavy monument section with broad bearing can therefore possess meaningful resistance to sliding even without adhesive. Smoothness, moisture, setting materials, surface contamination, and local contact conditions influence that resistance, so it should not be treated as a fixed universal value.

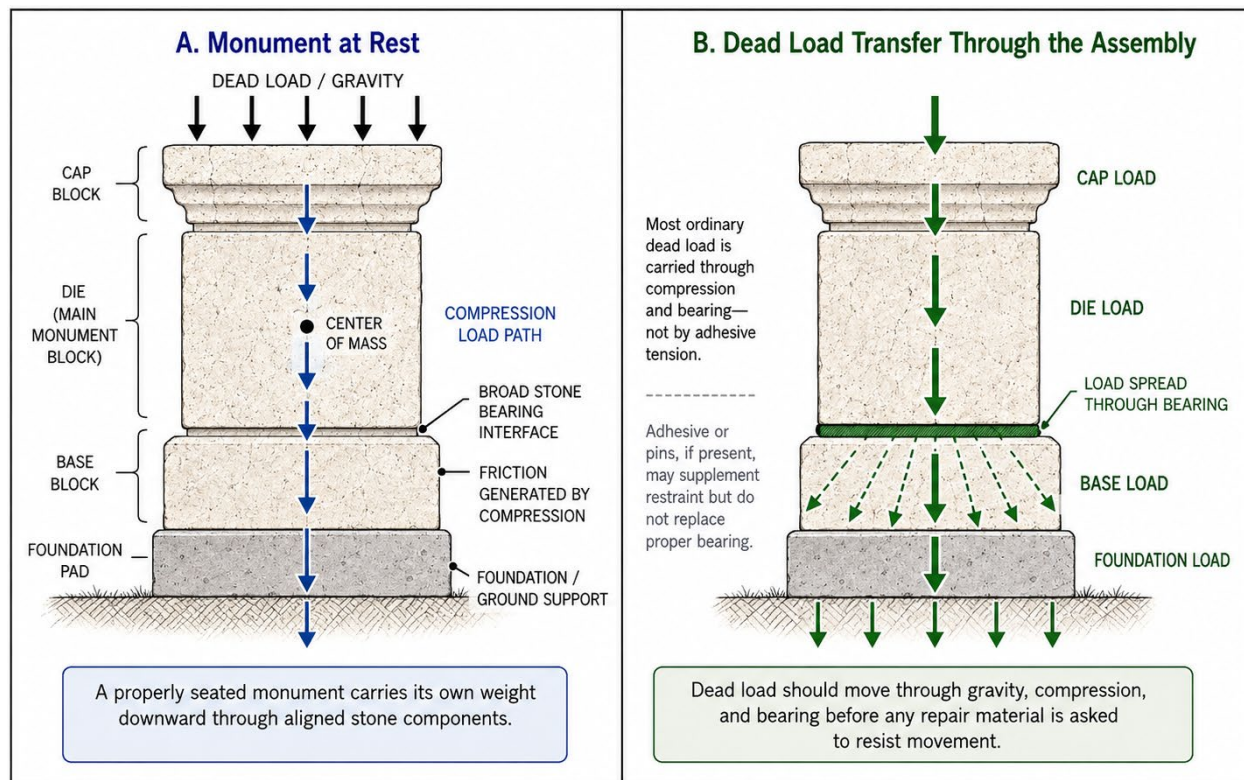
Structural adhesive adds shear-transfer capacity across the interface. Manufacturer lap-shear data are commonly cited for this reason, but real monument joints differ from standardized test specimens in surface condition, thickness, shape, and loading. Podany and colleagues specifically employed both shear and tensile testing in their marble adhesive research because commercial shear tests alone did not adequately represent the demands occurring in reassembled stone sculpture (Podany et al., 2001).

For a multi-piece cemetery monument, the practical question is how much additional shear restraint is actually required. If a broad, heavy die has adequate frictional resistance under ordinary conditions and needs primarily supplemental protection against accidental movement, localized adhesive restraint may be sufficient. If the component is light, narrow, unusually exposed, or geometrically inclined to move, stronger or mechanical restraint may be appropriate.

Again, the treatment decision begins with the load rather than the adhesive.

Before additional restraint is considered, the ordinary load path through a properly seated multi-piece monument should be understood. As Figure 4.1 illustrates, dead load can pass primarily through compression and bearing into the lower stone and foundation, leaving adhesive or mechanical reinforcement to address movements that gravity and geometry do not adequately control.

Figure 4.1: How a Multi-Piece Monument Carries Dead Load



Note. In a stable multi-piece monument, ordinary dead load travels primarily through stone-to-stone bearing, compression, and foundation support. This distinction is important because structural adhesive or mechanical restraint should supplement a sound load path rather than compensate for poor bearing or unstable support.

4.5. Rocking and Repeated Small Movements

Rocking deserves particular attention because a monument can experience repeated low-amplitude motion without suffering a single dramatic overload. Small changes in soil, foundation condition, thermal expansion, wind, or incidental contact may cause a component to pivot between different bearing points.

Repeated rocking can gradually damage both the stone and the repair materials. At each cycle, compressive stresses may shift toward one edge while the opposite side opens. Wedges may loosen or migrate. Brittle perimeter materials may crack. Adhesive may experience alternating shear and tension. Marble adjacent to a highly rigid bond may accumulate microdamage even though no single event exceeds the nominal strength of the joint.

A continuous adhesive interface may suppress visible rocking by increasing the stiffness of the connection. That can be beneficial if the underlying support is stable. If the rocking

originates from continuing foundation movement, however, the increased rigidity may merely transfer deformation upward until cracking develops elsewhere.

This illustrates an important conservation distinction between **stabilizing movement and concealing movement**. A repair that prevents a joint from opening visibly is not necessarily solving the mechanism that caused the joint to open.

The source of repeated movement should therefore be investigated before the connection is strengthened.

4.6. Bending in Tablet Stones

Thin upright tablet markers behave differently from broad stacked monument components because their geometry makes bending particularly important. A tablet embedded in the ground or set within a base acts, in simplified terms, as a vertical plate or beam subjected to its own weight, wind, handling, soil pressure near the base, and occasional lateral force.

A transverse fracture reduces the tablet's ability to transmit bending forces across the broken section. When the two pieces are adhesively rejoined, the repair must restore enough continuity for tensile and compressive stresses to cross the fracture. The adhesive is therefore performing a much more direct structural role than localized adhesive used within a compression-loaded horizontal monument joint.

During bending, one side of the tablet is placed into compression while the opposite side experiences tension. Near the central region between them, stresses change character. The precise distribution depends upon the tablet geometry and loading, but the conservation implication is straightforward: a repaired transverse break cannot be evaluated solely as a shear joint.

This is one reason a thin, closely fitting structural adhesive such as AKEPOX 5010 may be conceptually appropriate for a tablet fracture even though the same material might be used far more conservatively at a broad horizontal setting interface. The structural demand is different.

The condition of the marble on either side of the tablet break becomes especially important. A high-strength adhesive may restore the immediate joint so effectively that the next severe bending event creates a new fracture adjacent to it. That outcome does not necessarily mean the original repair was inappropriate; an extraordinary impact can exceed any reasonable treatment design. It does mean that the adhesive should not be evaluated solely by whether the original joint remains intact.

The amount and location of new stone loss must also be considered.

4.7. Tension, Peel, and Edge Effects

Adhesive joints generally perform most predictably when stresses are distributed over the bonded area. Edge conditions are more complicated because stress can become concentrated at the termination of a rigid bond.

Peel is especially significant. Rather than loading the entire adhesive surface simultaneously, peel tends to progressively open a joint from one edge. A comparatively modest applied force can therefore create high local stress near the advancing separation front. This behavior is familiar in bonded laminates and is equally relevant to stone fragments, projecting decorative elements, or monument components that can begin to lift from one side.

A large advertised tensile or shear strength does not necessarily predict peel performance. Nor does the average stress obtained by dividing applied force by total bonded area describe the local stress at the edge of a real joint.

Historic marble adds another complication because the surface immediately beside the adhesive may contain weathered grains, old microcracks, carved details, or earlier losses. If the adhesive itself resists peel strongly, the advancing crack may migrate into the marble rather than along the interface.

Bond termination should therefore be regarded as a potentially important stress zone. Excess adhesive extending unpredictably beyond the intended repair can enlarge or irregularly shape this zone, while aggressive cleaning of squeeze-out can damage already vulnerable edges. The objective should be a controlled joint geometry in which the extent of permanent bonding is known.

4.8. Overturning, Pins, and Tensile Restraint

Tall or narrow monument sections deserve more conservative structural evaluation because the consequences of overturning can be severe. In such cases, the argument for minimizing adhesive cannot be separated from the obligation to provide adequate safety.

A pin or dowel can substantially change the behavior of a horizontal monument interface by creating positive mechanical resistance to sliding and separation. Whereas gravity and friction cease to provide restraint once uplift occurs, a properly designed pin can continue to transfer forces across the opening joint. Structural adhesive spanning the interface can perform a related function, although its load transfer is distributed differently.

The choice between these systems cannot be decided from permanence alone. Drilling removes original material and creates a concentrated structural connection. Full-surface

adhesive preserves the absence of drilled holes but can create a broad permanent bond. Limited adhesive minimizes bonded area but may provide insufficient resistance for a tall or highly exposed element. In some configurations, a carefully designed mechanical connection may therefore be the least damaging adequate treatment even though it is more invasive locally.

This is where Technical Papers No. 2 and No. 3 converge. Conservation restraint should reduce **unnecessary** intervention, not necessary structural capacity.

The proper decision requires examination of monument geometry, stone integrity, the size and location of any potential drilled zone, expected load direction, failure consequence, public access, previous damage, and the possibility of achieving the required stability through bearing and mass alone.

4.9. Foundations, Settlement, and Load Redistribution

A monument does not end at its visible base. The soil and foundation beneath it ultimately resist every load transmitted through the stone. Changes below grade can therefore reorganize forces throughout the monument.

Differential settlement is particularly damaging because it introduces rotation. If one side of a foundation drops, the base may tilt and the components above it may lose uniform bearing. Contact becomes concentrated toward one edge, open joints appear on another, and the line of action of the monument's weight moves relative to the support footprint.

A flexible or partially unbonded assembly may reveal this process through opened joints and modest relative displacement. A highly rigidly bonded assembly may initially remain visually intact while carrying increasing bending and shear through the stone. Neither response is desirable; the important point is that stronger upper joints do not remove the underlying settlement.

Ground-supported headstone guidance from the National Park Service illustrates how persistent these environmental influences can be. Flooding, drainage, soil movement, coffin collapse or decay, animals, vandalism, and freeze-thaw are all identified as causes of shifting markers. NPS resetting guidance consequently relies on properly prepared support and compacted sharp gravel to improve drainage and resist movement rather than attempting to eliminate future settlement through rigid encasement (National Park Service, n.d.-e).

Multi-piece monuments may require different foundation systems, but the general lesson remains applicable. Adhesive selection should never be allowed to substitute for diagnosis of support conditions.

4.10. Monument Type Changes the Repair Problem

The phrase *historic marble monument* encompasses substantially different structural forms. A ground-supported tablet, tablet set into a base, low die-and-base monument, multiple-tier pedestal, obelisk, column, urn monument, sculptural figure, ledger, and complex architectural memorial do not present the same load paths or consequences of failure.

A ground-supported tablet derives stability primarily from embedment and soil support. Its principal adhesive problem is likely to involve fracture within the exposed stone rather than assembly of stacked components.

A die-and-base monument is largely compression-loaded under gravity but may require restraint against sliding or overturning. The quality of horizontal bearing becomes central.

A tall obelisk can contain multiple stacked sections while placing much greater significance on lateral stability because of its height. Small angular displacement at the base can produce substantial displacement at the top.

A column or narrow pedestal may develop high compressive stresses at limited bearing areas and can be susceptible to edge loading when out of plumb.

An urn, finial, or projecting architectural component may require direct tensile restraint because gravity does not necessarily stabilize it against every direction of movement.

These differences argue strongly against treatment rules based solely upon stone type and product. “Use epoxy on marble” and “never epoxy historic marble” are equally inadequate because neither identifies what the joint is doing.

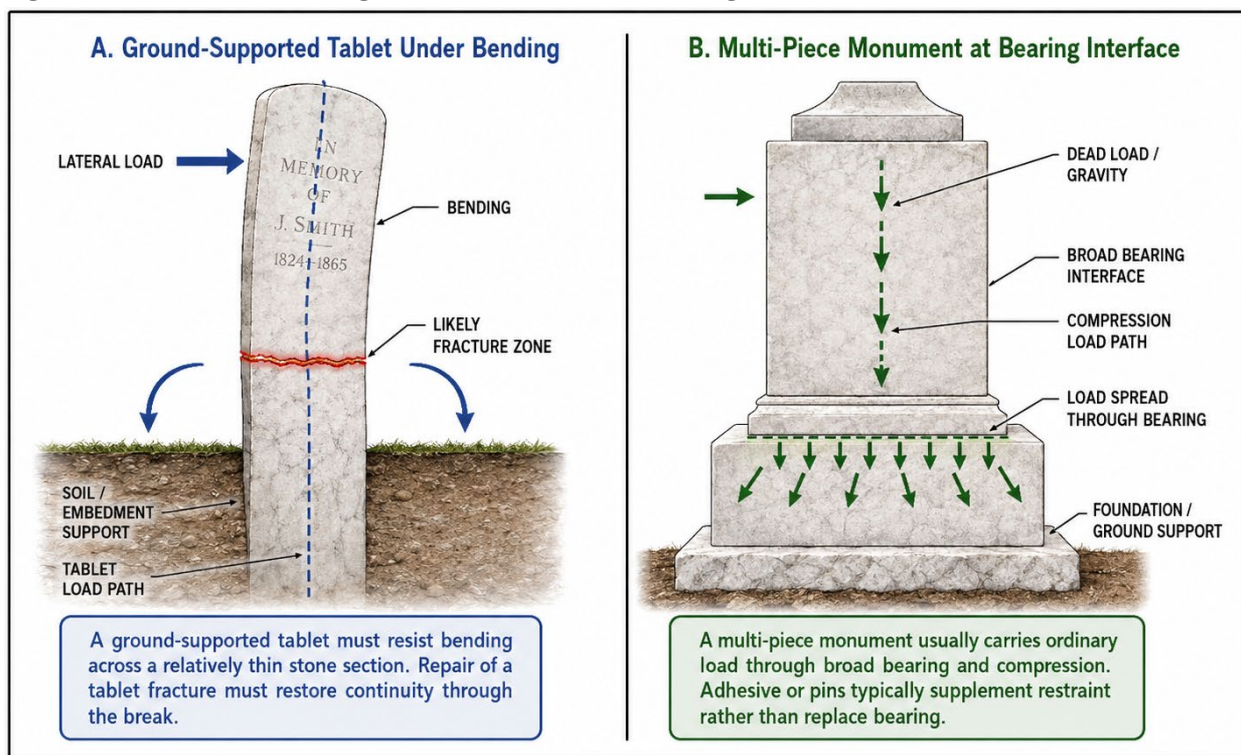
The first structural question should instead be: **How would this monument remain stable if no adhesive were present?**

The answer reveals which functions are already performed by gravity, geometry, bearing, friction, foundation support, and original construction. The next question is then: **Which remaining movement requires additional restraint?**

Only after those questions are answered does adhesive selection become technically meaningful.

Figure 4.2 compares the fundamentally different structural conditions presented by tablets and broad multi-piece monuments. A tablet fracture must restore continuity through a relatively thin bending member, whereas a broad monument component may already carry most of its dead load through compression and bearing; this difference is central to determining what the adhesive must actually accomplish.

Figure 4.2: - Tablet Bending Versus Monument Bearing



Note. Tablet fractures and broad monument joints do not perform the same structural function. A thin tablet repair must re-establish bending continuity through the fracture, whereas a broad monument interface already carries most ordinary dead load through stone-to-stone bearing and compression. This distinction explains why the same adhesive strategy should not automatically be applied to both conditions.

4.11. Adequate Stability Without Artificial Rigidity

Historic monument conservation frequently requires balancing two conditions that can appear contradictory. The repaired object must be stable enough to survive normal service, yet it should not be made unnecessarily rigid in ways that redirect movement into fragile original material.

This balance is familiar throughout building conservation. Historic structures often accommodate minor movement through joints, mortar, timber connections, or other interfaces that are less rigid than the principal structural materials. Cemetery monuments likewise need not behave as monolithic blocks when they were assembled from discrete components.

The objective is not intentional looseness. Joints should not rock, shift, or open under ordinary conditions. Rather, the repair should avoid transforming every interface into a fully

bonded structural connection when geometry and bearing already provide adequate support.

The same principle helps clarify the Gravestone Guardians limited-bond hypothesis. If a multi-piece monument is independently stable under dead load, properly aligned through controlled bearing, and resistant to ordinary sliding through mass and friction, localized Pratley Putty need not reproduce the capacity of a fully bonded Domo 10 or AKEPOX interface. Its required capacity is only that needed to supplement the existing structural system.

Whether the current GG configuration consistently achieves that objective remains an empirical question. The concept is mechanically plausible, but pad size, placement, marble condition, interface geometry, environmental aging, and movement must eventually be tested.

The merit of the approach therefore lies not in assuming that Pratley Putty is a conservation material by virtue of the way it is used. It lies in recognizing that **the amount of structural work assigned to the adhesive can itself be controlled.**

5. Historic Marble as an Adhesive Substrate

5.1. Marble Is Not an Inert Surface

An adhesive manufacturer can characterize a cured resin with considerable precision. Tensile strength, compressive strength, viscosity, working time, elongation, modulus, chemical resistance, and other properties can be measured under defined laboratory conditions. Historic marble is considerably less predictable.

Marble is a crystalline metamorphic rock formed primarily from recrystallized carbonate minerals, most commonly calcite and, in some marbles, dolomite. The rock may appear visually homogeneous, particularly where it was historically selected for fine monuments and sculpture, but at the microscopic level it is an aggregate of mineral grains with boundaries, orientations, impurities, pores, and existing discontinuities. Getty terminology describes marble broadly as a hard, dense crystalline metamorphic stone principally composed of calcium carbonate, while materials research demonstrates that its behavior is strongly influenced by grain fabric and crystallographic orientation (Getty Research Institute, n.d.).

Once marble is exposed outdoors for a century or more, the surface presented to an adhesive is no longer equivalent to freshly quarried stone. It may contain microcracks, loosened grains, soluble salts, embedded dirt, biological residues, previous coatings, old repair materials, moisture, and zones of differing porosity and cohesion. The fracture itself may expose comparatively sound interior material while only millimeters away the exterior face is severely weathered.

The substrate should therefore be understood as a variable component of the repair rather than a passive surface upon which adhesive is placed.

5.2. Marble Fabric and Anisotropy

Calcite is mechanically and thermally anisotropic. Its properties vary according to crystallographic direction. In a marble, thousands or millions of differently oriented calcite crystals interact to produce the macroscopic behavior of the stone.

This fabric matters because the grains do not all respond identically to environmental temperature change. Research into Carrara and other marbles has repeatedly demonstrated that thermal dilation depends upon crystallographic orientation, grain structure, microcracking, and rock fabric. The thermal expansion and contraction of neighboring grains can therefore be incompatible at their boundaries, producing internal stresses even in the absence of external structural loading (Siegesmund et al., 2000).

Different marbles respond differently. Grain size, grain-boundary geometry, preferred crystallographic orientation, pre-existing cracks, and mineral composition can significantly influence the degree of thermal deterioration. Research comparing marble varieties has found substantial directional differences in residual strain and degradation response, reinforcing the conclusion that “marble” cannot be treated as one mechanically uniform substrate (Siegesmund et al., 2021).

This variability has direct consequences for adhesive selection. Technical data derived from one marble cannot automatically establish the failure behavior of another, and observations from relatively fresh laboratory stone may substantially overestimate the capacity of a weathered cemetery marker.

5.3. Thermal Cycling and Intergranular Deterioration

The thermal behavior of calcite provides one of the principal explanations for the gradual granular deterioration commonly observed in exterior marble. Because differently oriented crystals expand and contract in different directions, repeated heating and cooling can generate stress incompatibilities at grain boundaries. Over many cycles, existing discontinuities may enlarge and new microcracks may develop.

The resulting deterioration can produce residual expansion even after the stone returns to its original temperature. In severe cases, loss of grain-to-grain cohesion produces the characteristic granular or sugar-like surface historically described as **sugaring**. Research on marble weathering specifically identifies anisotropic thermal dilation as a major contributor to this process, while studies of deteriorated marble show that microcracking can progressively increase stone volume and reduce structural coherence (Siegesmund et al., 2000).

Sugaring is particularly relevant to adhesive repair because an adhesive can bond only to the material actually present at the interface. If the outermost marble grains are poorly attached to the underlying stone, excellent chemical adhesion to those grains does not create an excellent structural connection to the monument. The repair may simply bond strongly to a mechanically weak surface layer.

This distinction can be described as a **substrate-limited bond**. Once adhesive strength and interfacial adhesion exceed the cohesive capacity of the receiving marble, additional adhesive performance provides little additional conservation benefit. Failure will occur within the stone.

That principle helps explain why very different adhesives can produce cohesive marble failure in laboratory testing. Podany and colleagues found marble failure not only with

conventional epoxy and polyester systems but also in many specimens bonded with Paraloid B-72. The adhesive category differed; the limiting material was often the marble itself (Podany et al., 2001).

For weathered cemetery marble, the threshold at which the substrate becomes limiting may be substantially lower.

5.4. Sugaring as a Structural Condition

In field practice, sugaring is sometimes discussed primarily in relation to cleaning. The concern is that aggressive brushing, pressure washing, or abrasion may remove loose mineral grains and accelerate loss of inscriptions or carved detail. National Park Service cemetery guidance appropriately identifies powdering, sugaring, flaking, and spalling as conditions that should be assessed before cleaning (National Park Service, n.d.-b).

For adhesive repair, however, sugaring has an additional significance. It is evidence that cohesion within at least part of the marble fabric has deteriorated. A surface that can be readily disrupted by mild mechanical action may not be able to receive concentrated structural stress from a rigid adhesive joint.

The degree and depth of deterioration are important. A thin weathered surface skin over sound interior marble presents a different condition from granular disintegration extending deeply into the fracture zone. A freshly exposed break can appear comparatively crystalline and sound even where the exterior faces are weathered. Conversely, an old fracture left exposed for decades may itself have undergone substantial granular deterioration.

This means that visual assessment of the monument exterior is not sufficient by itself to establish adhesive suitability. The practitioner should examine the actual surfaces that will carry load. Grain loss, softness, cracking, delamination, staining, moisture, previous treatment, and the ability of the surface to remain intact under gentle examination all contribute to understanding whether the stone can receive a structural bond.

The adhesive should never be expected to make severely disaggregated marble structurally sound merely by attaching to it.

5.5. Microcracks and Hidden Weakness

Many of the defects governing stone failure are too small to be visible during ordinary field examination. Microcracks can occur along grain boundaries or through individual grains and may exist well before a visible fracture develops. Their number, orientation, and connectivity influence stiffness, strength, porosity, moisture movement, and the direction in which future cracks propagate.

Ultrasonic research on marble has demonstrated that degradation and loosening of crystal contacts can be detected through changes in ultrasonic velocity, illustrating that apparently intact marble can possess substantial internal structural differences (Siegesmund et al., 2021).

Adhesive repair interacts with these hidden defects in two ways. First, resin may penetrate some accessible cracks or pores near the interface and locally increase cohesion. Second, the repaired zone may become stiffer and stronger than neighboring untreated material. Under future loading, the stress concentration associated with the joint may activate pre-existing microcracks beyond the resin-affected region.

The resulting fracture can appear to have been “caused by the epoxy” even when the actual mechanism involves an existing weak zone subjected to redistributed stress. This distinction does not absolve the adhesive system; a treatment that predictably redirects force into damaged stone may still be inappropriate. It does emphasize that failure interpretation requires consideration of the substrate condition rather than assuming that intact adhesive beside broken marble proves only that the resin was excessively strong.

A conservation-oriented experiment should therefore document not merely whether the stone failed, but where the failure originated and how far it propagated relative to the bond.

5.6. Moisture and the Marble-Adhesive Interface

Exterior cemetery marble exists within a persistent moisture cycle. Rain, dew, snow, soil moisture, capillary uptake, humidity, and condensation can all affect the stone. Water may occupy pores and microcracks, dissolve and transport salts, support biological growth, and influence freeze-thaw behavior.

Moisture also matters during bonding. Adhesives differ substantially in their tolerance of damp substrates. Some formulations are specifically designed to adhere to slightly moist mineral surfaces, while others require comparatively dry conditions for reliable performance. Manufacturer statements on moisture tolerance should be treated as product-specific rather than generalized across all epoxies or putties.

Even where initial adhesion is successful, the long-term moisture behavior of the repaired zone deserves attention. A cured polymer generally possesses a different permeability and moisture-transport behavior from marble. A continuous resin layer can therefore alter the pathways through which water moves across a joint. In a limited-bond system, more of the original mineral interface may remain available for vapor and liquid movement, although the practical consequence will depend upon perimeter materials and joint geometry.

The problem should not be oversimplified into a rule that the stone must always “breathe.” Moisture transport in porous stone is governed by several interacting processes, and marble porosity can vary substantially with deterioration. The appropriate conservation concern is whether the repair produces a localized moisture condition that differs sufficiently from the surrounding stone to encourage staining, salt concentration, frost susceptibility, or differential deterioration.

The Getty Conservation Institute's broader stone-conservation research emphasizes the importance of moisture, salts, frost weathering, treatment effects, and long-term field performance when evaluating interventions in porous stone (Doehne & Price, 2010).

Adhesive selection should therefore consider not only whether the bond remains intact when wet but how the completed repair alters the environmental behavior of the stone around it.

5.7. Freeze-Thaw and Existing Fracture Networks

Freeze-thaw damage is frequently invoked in cemetery preservation, sometimes too casually. Water does not automatically destroy every stone simply because the temperature falls below freezing. Damage depends upon saturation, pore structure, permeability, existing cracks, freezing conditions, and the ability of water and ice to redistribute.

Nevertheless, an exterior monument in a cold climate experiences repeated conditions in which moisture and temperature can interact with existing defects. Open cracks and poorly closed joints admit water; deterioration can increase fissure porosity; and repeated environmental cycles can enlarge damage already initiated through thermal or mechanical processes.

Adhesive repair changes these pathways. A successfully closed fracture may reduce direct water entry through the original break, which is beneficial. At the same time, a comparatively impermeable bonded zone can redirect moisture toward neighboring cracks or edges. A perimeter seal may further alter this behavior.

The relevant research question is therefore not whether epoxy is categorically “bad because it traps moisture,” a formulation too broad to be useful. It is how a particular joint geometry, adhesive extent, and perimeter treatment influence moisture distribution over repeated environmental cycles.

This is one of the reasons outdoor aging studies are essential before laboratory adhesive rankings are translated into cemetery practice.

5.8. Salts and the Bonding Substrate

Soluble salts present another variable at the stone-adhesive interface. Salts can reach monuments through soil, deicing materials, atmospheric deposition, previous cleaning agents, biological processes, incompatible mortars, or other sources. As moisture conditions change, salts dissolve, migrate, crystallize, and rehydrate according to their chemistry and local environment.

For adhesive repair, salt contamination creates at least three concerns. First, crystalline deposits and contaminated surface material can interfere with reliable adhesion. Second, continued crystallization within pores near a bonded zone may progressively weaken the stone even though the polymer itself remains unaffected. Third, a relatively impermeable repair may alter local drying patterns and encourage salt accumulation near the edges of the treated region.

These processes are especially relevant where a strong adhesive is bonded to a shallow zone that later becomes weakened through salt crystallization. The adhesive may remain intact while a layer of marble separates beneath it.

The practical implication is that adhesive performance cannot be separated from diagnosis of active deterioration. A monument suffering from persistent moisture and salt movement requires attention to those mechanisms; increasing bond strength does not neutralize them.

5.9. Biological Growth and Surface Condition

Historic cemetery monuments commonly support algae, cyanobacteria, fungi, lichens, mosses, and associated organic residues. Their significance to adhesive repair is less direct than their visual presence might suggest, but they can influence surface preparation and diagnosis.

An adhesive should bond to mineral substrate rather than to a detachable biological film. The same is true of accumulated dirt, old setting compound, deteriorated mortar, wax, coatings, previous adhesives, and other intervening materials. Yet aggressive removal of contamination can itself damage weathered marble.

This creates another conservation balance. Surface preparation sufficient for dependable adhesion is necessary; preparation so aggressive that sound original stone is removed in pursuit of an idealized clean surface is not.

The proper level of preparation will vary with the repair. A thin structural fracture demands intimate contact and clean fracture surfaces. A localized putty restraint within a broad

setting joint may tolerate somewhat different surface geometry. Mineral grout requires yet another substrate condition.

The essential principle is that **adhesive strength reported for clean laboratory substrates should not be assumed on historically weathered, biologically colonized, or previously treated marble.**

5.10. Previous Repairs as Part of the Substrate

Many historic monuments have been repaired repeatedly. Portland cement, gypsum, sulfur, lead, iron cramps, copper, bronze, steel, polyester resin, silicone, construction adhesive, epoxy, caulk, mortar, and improvised fillers can all be encountered in cemetery work.

These materials may affect new adhesive performance even after obvious residues have been removed. Old resin can remain within pores. Iron corrosion can create cracks and staining. Cementitious repairs can leave rigid accretions or salt contamination. Previous pin holes may reduce available sound stone for future drilling. Silicone contamination can seriously interfere with adhesion. Old fractures may contain dirt and biological material that cannot be completely removed without widening the break.

The substrate presented to a new repair is therefore sometimes a composite of original marble and previous intervention.

This history must be incorporated into the failure hierarchy. If a previous epoxy repair has already consolidated part of the fracture, applying new adhesive beside it may create an irregular zone of stiffness. If old pin holes exist, reusing them may preserve original material compared with drilling additional holes, provided their location and condition remain structurally suitable. Getty conservators have used precisely this logic in stone sculpture treatment, developing reassembly systems that deliberately employed existing holes while avoiding additional drilling and minimizing new adhesive (Daehner & Shelley, 2018).

Previous work should thus be treated neither as contamination to be erased automatically nor as a condition that must be retained regardless of performance. It is part of the existing structural history of the monument.

5.11. Fracture Surfaces Versus Weathered Exterior Surfaces

A freshly broken marble surface and a century-weathered exterior surface can possess markedly different characteristics. The fracture may reveal relatively clean crystalline

material with good cohesion and high surface area. The exterior may be rounded, soiled, sugared, polished, crusted, or previously treated.

This distinction is central to tablet repair. When two fragments fit closely along a fresh or protected fracture, the adhesive may engage relatively sound interior marble even if the monument's exterior displays moderate weathering. The narrow joint also limits the visible and volumetric presence of polymer.

By contrast, attaching a new element directly to a deteriorated exterior face requires the adhesive to transfer load through the weathered surface zone. The apparent condition of that surface may therefore govern the capacity of the entire repair.

This helps explain why product recommendations should be linked to joint type rather than stone name alone. A formulation suitable for a well-fitting internal fracture in marble may be inappropriate for a broad bond against a weak weathered face of the same monument.

5.12. Resin Penetration and the Altered Zone

Low-viscosity adhesives can enter pores and microcracks near the bonded interface. This penetration may improve adhesion by increasing mechanical interlock and consolidating weak grains. It may also create an altered zone in which polymer-impregnated marble behaves differently from untreated stone.

The conservation significance depends upon depth, continuity, stone porosity, resin properties, and the condition of the receiving substrate. Penetration into sound marble may be limited. In highly microcracked or sugared marble, greater uptake may occur.

The altered zone can be beneficial in the narrow sense that loose material becomes better connected. The concern arises when a strong transition develops between resin-rich stone and weak untreated marble. Future failure may occur at the boundary between the two rather than within the original fracture.

This phenomenon complicates the desire for adhesive failure at the exact repair interface. A resin that penetrates well may eliminate a distinct adhesive-stone boundary near the surface, replacing it with a gradient of polymer-influenced material. Removal then becomes correspondingly more difficult.

Intervention-layer systems using thermoplastic acrylics have partly been proposed to control this problem by isolating less reversible epoxies or polyesters from direct penetration into the marble. Podany and colleagues evaluated Paraloid B-72 in precisely this role, seeking to retain structural capacity while increasing reversibility of the overall bond (Podany et al., 2001).

Whether such systems are durable under long-term cemetery exposure remains an important question for this paper's later experimental program.

5.13. Stone Condition Establishes the Ceiling for Adhesive Performance

The interaction between weathered marble and structural adhesive can be summarized through a simple principle: **the effective strength of the repaired joint cannot be considered independently from the weakest material through which the load must pass.**

If an adhesive possesses a tensile capacity far above the cohesive strength of deteriorated marble, increasing adhesive strength further does not increase the amount of historic stone the joint can safely mobilize. It may simply ensure that failure occurs elsewhere.

This concept is familiar in other bonded systems but has particular importance in conservation because the weaker substrate is also the irreplaceable component. The highest-performing adhesive in fabrication terms may therefore provide no preservation advantage once the stone becomes the limiting material.

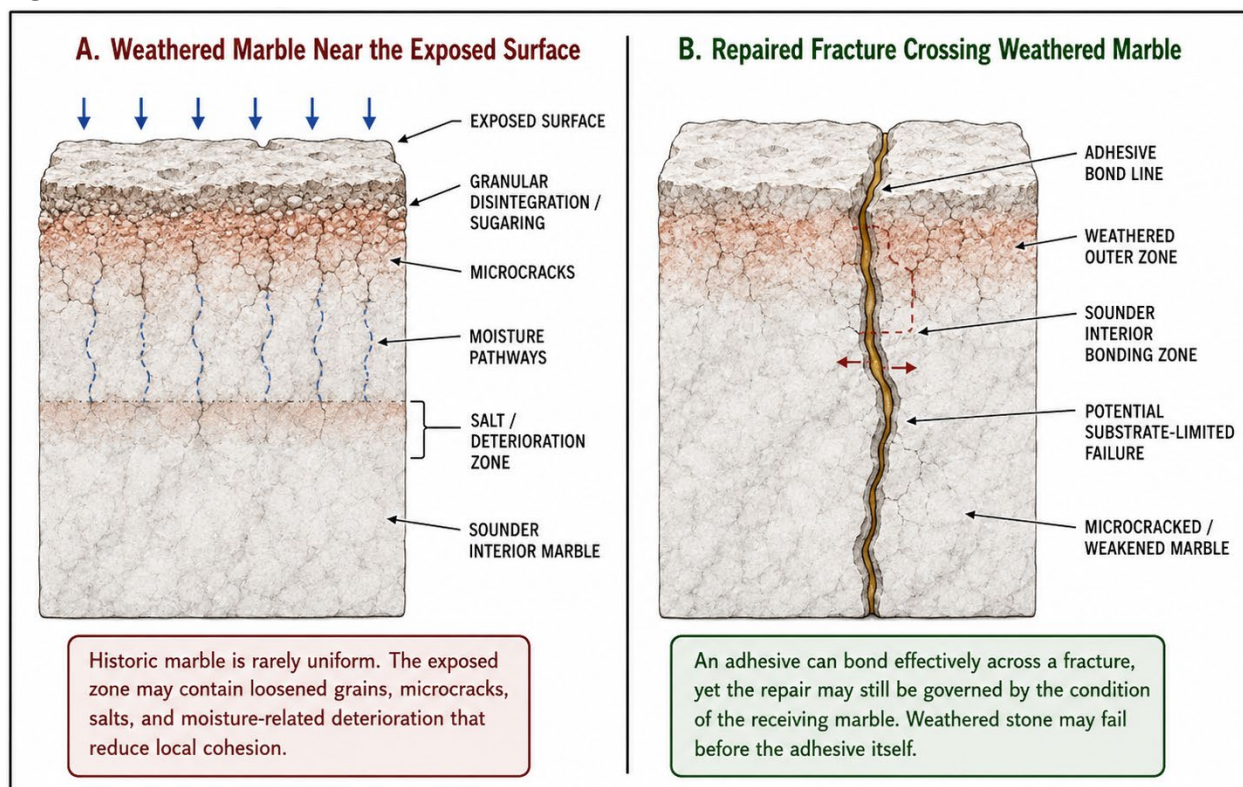
The implication is not that deteriorated marble should always receive a weaker adhesive. A weak adhesive that repeatedly fails under ordinary conditions can necessitate repeated handling and treatment, each of which risks additional loss. Nor should severely disaggregated stone automatically be consolidated so that a stronger adhesive can be used. Consolidation introduces its own compatibility, penetration, color, moisture, and retreatability concerns.

The appropriate response is to determine whether the stone possesses enough cohesive capacity for the proposed structural role at all. If it does not, the treatment concept may need to change.

A larger bearing area, different orientation, mechanical support independent of the weak surface, reduced loading, shelter, replacement of a nonhistoric component, or acceptance that the monument cannot safely be reassembled in its previous configuration may sometimes be more responsible than attempting to achieve adequate bond strength through increasingly aggressive intervention.

The mechanical condition encountered by an adhesive is rarely uniform throughout historic marble. Figure 5.1 illustrates how surface weathering, granular disintegration, microcracking, moisture pathways, and comparatively sound interior stone can coexist within the same treatment zone, making local substrate condition more important than the generic designation of the material as marble.

Figure 5.1: Weathered Marble as an Adhesive Substrate



Note. Weathered marble is not a uniform adhesive substrate. Surface sugaring, thermally induced microcracking, salts, and moisture pathways can reduce the capacity of the stone immediately adjacent to a bond. For this reason, the behavior of a repaired joint may be controlled by the condition of the receiving marble rather than adhesive strength alone.

5.14. Condition Is a Continuum, Not a Pass-Fail Category

Field descriptions such as *sound*, *weathered*, *sugaring*, and *friable* are useful but can imply sharper boundaries than actually exist. Marble deterioration commonly occurs along a continuum. A stone may be sound in one region, moderately granular in another, and severely disaggregated along an exposed edge. The same fracture may cross multiple conditions.

This variability is one reason rigid treatment recipes perform poorly in historic monument conservation. A rule stating that AKEPOX 5010 is suitable for marble tablet fractures might be reasonable only when accompanied by conditions concerning the marble's ability to receive the bond. Conversely, a blanket prohibition based upon the existence of weathering somewhere on the monument could exclude structurally viable repairs unnecessarily.

Assessment should therefore focus on the material immediately associated with the load path. Where will adhesive be placed? What stone surrounds the intended bond? Where will

tensile or shear forces enter the marble? Are there nearby cracks, losses, thin carved sections, sugared edges, or previous holes? How much material would be lost if cohesive failure occurred around the repair?

These questions connect substrate assessment directly to failure hierarchy.

5.15. Implications for Akepox 5010 Tablet Repairs

The use of Akepox 5010 for closely fitting tablet fractures should be evaluated within this substrate framework rather than through a general endorsement of epoxy. Several features of the application can be favorable: the fracture surfaces may expose relatively sound interior marble; close fit allows a thin bond line; adhesive volume can be limited; and the joint restores continuity across a pre-existing break rather than creating a new connection between previously separate historic surfaces.

The principal conservation concern remains the potential for a future bending or impact event to cause cohesive marble failure adjacent to the repaired joint. Where the adhesive and interface possess greater capacity than the weathered tablet, the old fracture may remain intact while a new fracture develops nearby.

This possibility should be acknowledged explicitly. The relevant treatment question is whether the repaired tablet can reliably withstand ordinary service without invasive internal reinforcement and whether the probable damage associated with an extreme future event is acceptable compared with alternative treatments such as pinning.

Where marble adjacent to the break is severely sugared, laminated, cracked, or structurally weak, the same repair strategy becomes less defensible because the adhesive would be transferring force into an inadequate substrate. The product has not changed; the conservation relationship has.

This distinction is essential to any future Gravestone Guardians treatment guideline.

5.16. Implications for Pratley Putty in Multi-Piece Monuments

Pratley Standard Setting Putty presents a different substrate relationship because it is ordinarily used in a thicker mass and, in the Gravestone Guardians approach examined here, at localized locations within a multi-piece assembly.

A putty can conform to irregular surfaces and provide substantial mechanical engagement. Its thickness and stiffness, however, mean that it should not be regarded simply as a thicker version of a thin fracture adhesive. The cured pad becomes a discrete structural element between the stones.

If the surrounding marble is sound and the pad is positioned within a broad, well-supported region, it may provide useful restraint while the stone remains primarily compression-loaded. If the same pad is placed close to a weakened edge, thin wall, sugared surface, or historic fracture, the concentrated restraint may create a less favorable failure path.

The conservation argument for Pratley therefore rests heavily upon placement and limited area. It does not depend upon demonstrating that the cured putty is mechanically weaker than the marble.

This is an important distinction because published manufacturer information for many epoxy putties is insufficient to establish all properties relevant to historic marble conservation. Even if comprehensive tensile and modulus data were available, those values would still not determine suitability without information about the actual weathered substrate and joint geometry.

The GG limited-bond model should therefore be tested as a **system**, not merely by testing isolated Pratley specimens.

5.17. Why Laboratory Marble Is Necessary but Insufficient

Controlled laboratory specimens are indispensable because meaningful comparison requires consistency. Adhesives cannot be ranked experimentally if every specimen has a different fracture geometry, degree of weathering, moisture content, and stone fabric.

The danger arises when controlled specimens are assumed to represent historic monuments without qualification.

Research on marble degradation demonstrates that thermal history, moisture, microcracking, rock fabric, and mineral orientation can materially alter physical behavior (Siegesmund et al., 2000). A freshly cut marble coupon is therefore best understood as a reference condition rather than a direct surrogate for a weathered nineteenth-century headstone.

An effective experimental program for this paper should ultimately include both controlled sound marble and naturally weathered sacrificial material where ethically and legally available. Artificial aging may supplement these specimens but should not be assumed to reproduce the full complexity of natural exposure.

The purpose of testing should likewise extend beyond maximum force. A specimen that fails at a high load by removing a deep cone of marble around the adhesive presents a

different conservation outcome from one that fails at a lower load with minimal substrate loss.

Stone loss, fracture path, retreatability, and environmental aging should therefore be recorded alongside conventional strength measurements.

5.18. The Substrate Determines Whether the Repair Philosophy Is Viable

The broader argument of this paper depends upon a simple limitation: no clever arrangement of adhesives, wedges, grouts, or setting compounds can make severely deteriorated stone behave like sound marble without introducing additional intervention.

Failure hierarchy can redistribute risk, but it cannot eliminate the underlying weakness of the substrate. Limited bonded area can reduce the total force transmitted through adhesive, but the remaining load still enters the stone somewhere. Stable bearing can reduce tensile demand, but the bearing surface must possess enough compressive integrity to carry the weight. Mechanical reinforcement can bypass a weak interface, but the surrounding stone must remain sound enough to receive the reinforcement.

Material assessment is therefore not merely a preliminary step before choosing the adhesive. It establishes whether the proposed repair concept is viable at all.

This is particularly important when evaluating historical monuments through photographs or generalized rules. Two apparently identical marble tablets of the same age can respond differently because they came from different quarries, were cut in different orientations, experienced different moisture exposure, were cleaned differently, or possess different internal fracture histories. Two pieces of the same monument may themselves exhibit markedly different conditions.

The responsible treatment decision must remain object-specific.

5.19. From Marble Condition to Joint Design

Chapters 3, 4, and 5 together establish three connected propositions.

The first is that conservation should consider the **failure hierarchy of the complete repair**, not merely the strength of an individual adhesive.

The second is that monument components carry different combinations of compression, shear, bending, tension, and overturning demand according to their geometry and support. Adhesive should therefore be assigned only the structural role actually required.

The third is that historic marble is a variable, environmentally altered substrate whose cohesive condition may govern the strength and failure mode of the repaired assembly regardless of the nominal capacity of the adhesive.

Taken together, these propositions substantially narrow the conditions under which a product-based recommendation can be meaningful. AKEPOX 5010, Pratley Standard Setting Putty, Tenax Domo 10, HXTAL NYL-1, Paraloid B-72, polyester mastic, mineral grout, or any other material should not be described simply as suitable or unsuitable for historic marble. Suitability exists only in relation to a defined substrate, joint geometry, load path, environment, and desired failure hierarchy.

The next stage of the paper can therefore move from principles to the geometry of the joint itself. Bond-line thickness, fracture fit, contact area, adhesive volume, discontinuous versus continuous bonding, gap filling, and the position of the bond relative to edges and existing defects determine how the material properties examined later are translated into actual stresses within the monument.

Only after that relationship is understood does comparison of individual adhesives become genuinely useful.

6. Joint Geometry and Its Influence on Repair Performance

6.1. The Adhesive Does Not Act Independently of the Joint

The preceding chapters established that the mechanical properties of an adhesive cannot be evaluated independently of the condition of the marble, the loads acting upon the monument, or the intended failure hierarchy of the repair. Joint geometry adds another equally important variable. The same adhesive can behave very differently when applied as a thin film within a closely fitting fracture, as a thick mass filling missing material, as a continuous layer beneath a monument die, or as several discrete pads used primarily to resist displacement.

This distinction is central to the argument of this paper because discussions of historic-stone adhesives often proceed as though a material possesses a single structural character. Akepox 5010 may be described as a strong epoxy, Pratley Standard Setting Putty as a rigid epoxy putty, and Paraloid B-72 as a comparatively reversible acrylic. Those descriptions are chemically useful but mechanically incomplete. Once incorporated into a repair, each material becomes part of a joint whose width, shape, area, position, and loading determine how the adhesive's properties are translated into stresses within the historic stone.

Conservation research on marble adhesives supports this emphasis on geometry. Jorjani and colleagues specifically examined both interfacial fracture toughness and bond-line width across thermoplastic and thermosetting adhesive systems, recognizing that adhesive performance cannot be understood from bulk strength alone. The study included Paraloid B-72, B-48N, HXTAL NYL-1, Epo-Tek 301-2, Akepox 2000, Marmorkitt 1000, and combined systems. Several thermoplastic adhesives proved mechanically viable under the conditions tested, but differences in bond width and fracture behavior remained significant variables in interpretation.

Joint geometry should therefore be treated as part of material selection rather than as a workmanship detail considered only after an adhesive has been chosen.

6.2. Closely Fitting Fractures

A closely fitting fracture represents the condition most commonly associated with structural adhesive repair of tablet stones. The broken surfaces retain much of their original topography and, when properly aligned, can often be returned to near-original contact. The adhesive occupies a relatively small volume between irregular mineral surfaces rather than replacing a substantial portion of missing stone.

Several characteristics of this geometry are favorable. First, the thin bond line limits the volume of polymer introduced. Second, the irregular fracture surfaces provide considerable microscopic and macroscopic surface area. Third, the topography of the break may provide some mechanical interlock independent of the chemical adhesion of the resin. Finally, accurate reassembly restores the original geometry of the tablet with comparatively little loss compensation.

These characteristics do not make a thin adhesive joint harmless. A sufficiently strong bond can still cause future fracture to migrate into adjacent marble. The importance of the thin joint lies instead in limiting how substantially the polymer changes the geometry of the repaired section. The resin occupies the existing fracture rather than becoming a large replacement element.

AKEPOX 5010 is particularly relevant to this geometry because its manufacturer describes the material as gel-like while noting that thin adhesive joints can nevertheless be achieved. The current technical data sheet reports very low shrinkage during curing and identifies the product for weather-resistant bonding of marble and other natural stone.

For Gravestone Guardians' tablet repairs, this geometry is one of the principal reasons AKEPOX 5010 and Pratley Putty should not be regarded as interchangeable simply because both cure into rigid polymer systems. The former can be used as a relatively thin fracture adhesive; the latter is intentionally selected where a mouldable three-dimensional mass is useful.

6.3. Irregular and Poorly Fitting Fractures

Not every broken tablet or monument component returns to intimate contact. Small chips may have been lost during the original break. Edges can be eroded after years of exposure. Previous repair materials may have altered the surfaces. Repeated movement may have abraded high points, while sugaring can remove grains from the interface.

As fit deteriorates, the adhesive is increasingly required to perform two different functions: bonding the surviving stone and replacing missing volume. These functions should not be assumed to require the same material properties.

A resin that performs exceptionally in a thin bond line may not be desirable in a thick section. Larger volumes can increase the amount of polymer participating in dimensional change, heat generation during cure, thermal movement, and future fracture transfer. Thick resin masses can also create visually and mechanically distinct regions whose properties bear little resemblance to the marble.

The presence of a gap therefore should not automatically be interpreted as an instruction to add more of the same adhesive until the void is filled. Depending upon the location and structural role of the missing material, a separate fill material or mineral repair mortar may provide a better solution. The adhesive can remain confined primarily to the surfaces that must be joined, while loss compensation performs a different function.

This separation mirrors the broader principle developed in Chapter 3: bonding, bearing, filling, and weather protection should be treated as distinct roles whenever practical.

6.4. Bond-Line Thickness

Bond-line thickness influences both stress distribution and the practical behavior of an adhesive. Very thin bond lines tend to restrict the volume of polymer and may produce high apparent rigidity because little adhesive thickness is available to deform. Thick joints introduce more polymer and can accommodate greater geometric irregularity, but they also magnify the importance of the polymer's shrinkage, stiffness, thermal expansion, creep, and aging behavior.

There is therefore no universal conservation rule that the thinnest possible joint is always the safest. A joint so tight that most adhesive is squeezed away can contain dry regions and insufficient wetting. Conversely, intentionally widening a sound historic fracture merely to provide a thicker adhesive layer removes original material and should generally be avoided. The appropriate bond width arises from the existing fracture geometry and the rheological characteristics of the selected adhesive.

The treatment objective should be **continuous wetting with the minimum bond volume necessary to establish a reliable joint**, not an arbitrarily predetermined thickness.

This principle has direct implications for surface preparation. Manufacturer instructions for industrial stone adhesives often recommend roughening surfaces to increase bonding. AKEPOX 5010, for example, instructs users to clean and slightly roughen the surfaces to be bonded. Such guidance makes sense in commercial fabrication where maximizing bond performance may justify mechanical preparation of newly fabricated stone. In historic conservation, deliberate roughening of an original fracture should not be adopted automatically. The irregular fracture already provides considerable surface texture, and removing original marble merely to optimize resin adhesion may conflict with minimum-intervention principles.

The distinction between manufacturer preparation recommendations and conservation preparation requirements should remain explicit throughout this paper.

6.5. Bonded Area as a Structural Variable

If bond-line thickness controls the depth of the adhesive layer, bonded area controls the extent over which the polymer can transfer forces into the stone. Both variables influence the total mechanical capacity of the joint.

The effect of area is easiest to visualize in a broad horizontal monument interface. A continuous adhesive layer covering most of the underside of a die creates a large connection capable of transmitting shear, tension, and bending between components. Even if the adhesive's nominal strength is moderate, the total bonded area can allow substantial force to develop before separation occurs.

Localized pads of the same material produce a different connection. The upper component may remain fully supported in compression through bearing, while adhesive restraint acts only at selected regions. Less of the historic interface is permanently bonded, and the total tensile or shear force that can be transmitted through the polymer is correspondingly constrained by geometry.

This does not mean that percentage of bonded area can simply be converted into percentage of structural strength. Stress concentrations, edge effects, pad shape, stone variability, and nonuniform loading prevent such a simplistic relationship. A small pad can develop high local stress, while some portions of a broad continuous bond may contribute relatively little to resistance under a particular load.

The important point is more fundamental: **bonded area is not merely the result of how generously the adhesive happens to be applied. It is a treatment-design decision.**

For conservation work, the practitioner should be able to explain why the chosen bonded area is necessary.

6.6. Full-Surface Bonding

Full-surface bonding is common in stone fabrication because it maximizes contact and distributes load over a large interface. Tenax's current Domo 10 technical instructions, for example, direct the user in certain fabrication applications to distribute the product homogeneously and ensure total surface coverage.

That instruction illustrates the difference between fabrication and conservation objectives particularly well. For newly manufactured stone assemblies, comprehensive coverage can improve consistency and reduce voids. For historic multi-piece monuments, however, full coverage also creates the greatest possible permanent bonded area.

Such a treatment may still be justified where broad structural coupling is required. It should not, however, become the default merely because complete coverage represents ideal adhesive practice in another industry.

A full-surface bond changes a bearing interface into a composite joint. Forces that previously might have been relieved through slight opening, sliding, deterioration of setting material, or adjustment at the interface can be transmitted into the stone. Future dismantling becomes correspondingly more difficult because access to the adhesive is largely confined to the perimeter.

For low, broad, stable monument sections, this amount of structural coupling may exceed what is required. For other configurations, particularly mechanically complex or highly exposed elements, it may be justified. The treatment decision should emerge from structural demand rather than application habit.

6.7. Localized Adhesive Pads

Localized adhesive pads provide a means of deliberately separating support from restraint. Their conservation advantage is not that a pad is inherently benign, but that permanent bonding can be confined to areas where its contribution is needed.

Pad placement matters greatly. Areas near thin edges, carved elements, corners, previous cracks, drilled holes, or visibly deteriorated marble are poor candidates for concentrated structural restraint. More substantial interior regions generally provide a larger volume of surrounding stone into which loads can distribute.

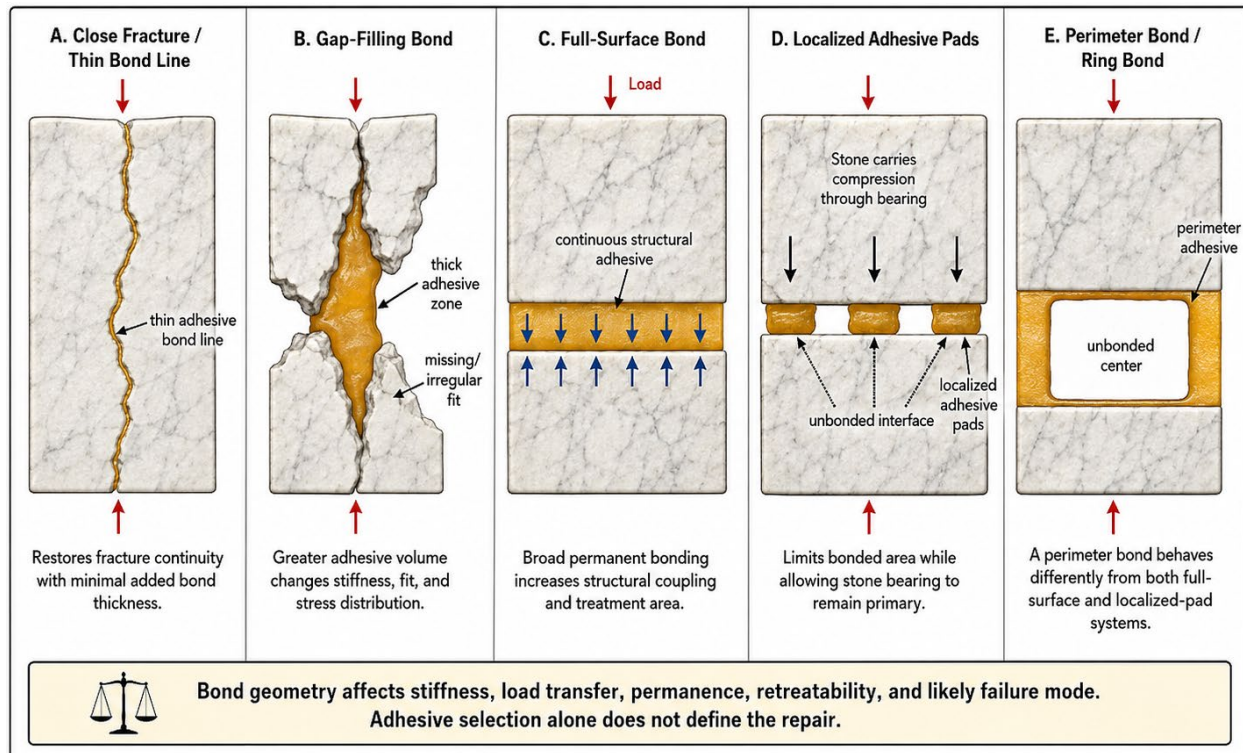
Pad shape may also affect stress concentration. Sharp corners within rigid bonded regions can produce different local conditions from rounded or irregularly feathered boundaries. The effects in historic marble have not been sufficiently quantified to justify a prescriptive pad geometry, but the issue deserves inclusion in the experimental program proposed later in this paper.

The same is true of pad thickness. A very thick mass becomes progressively more significant as an intermediate structural component, while an extremely thin pad may be ineffective where the surfaces do not meet closely. Pratley Standard Setting Putty is useful partly because it can accommodate irregular space, but that capability should not be interpreted as permission to support entire monument sections on large masses of cured epoxy putty.

In the Gravestone Guardians limited-bond model, pad geometry should therefore be evaluated in conjunction with lead bearing points. The putty restrains; the lead and stone interface support.

The significance of joint geometry is summarized in Figure 6.1. Close-fitting fractures, irregular gaps, broad continuous bonds, localized adhesive pads, and perimeter bonds expose the adhesive and surrounding stone to different stress-transfer conditions even when the same resin is used.

Figure 6.1: Bond Geometry Changes the Repair



Note. The adhesive can behave very differently depending on where it is placed, how much interface it occupies, and whether the stone is carrying load through fracture continuity, broad bearing, localized restraint or perimeter coupling. For this reason, repair geometry is a conservation variable, not merely an installation detail.

6.8. Continuous Perimeter Bonds

A particularly problematic geometry can arise when adhesive is applied continuously around the perimeter of a monument interface while the center remains unbonded. This configuration may appear conservative because less adhesive is used than in a full-area bond, but its mechanics deserve careful consideration.

The perimeter is frequently where bending and overturning stresses are greatest. When an upper component begins to rock, lift, or rotate, the edges of the joint experience the earliest changes in contact pressure. A strong adhesive band concentrated precisely at those edges may therefore receive substantial tensile or peel loading. The configuration can also restrict access to the interior during future retreatment.

A perimeter-only structural adhesive should not be confused with a perimeter setting or weather joint. The latter may intentionally be replaceable and less structurally significant. Combining the two roles through a rigid thermosetting adhesive can defeat the sacrificial logic developed in Chapter 3.

Localized restraint placed somewhat inward from fragile edges may therefore offer a different failure hierarchy from a continuous rigid perimeter band, provided the geometry allows the adhesive locations to remain documented and eventually accessible.

6.9. Fracture Terminations and Stress Risers

The ends of a repaired fracture deserve special attention. Even where the adhesive bond is uniform, the transition from repaired material to unbroken stone creates a change in local geometry and stiffness.

If a fracture terminates within the stone rather than passing completely through it, injecting or bonding the crack can create a region in which the original crack tip is mechanically altered. Future loading may reactivate the old crack, extend it, or initiate a new crack nearby depending upon local defects and stress orientation.

Similarly, an adhesive line that ends abruptly near an exposed edge can create a sharp transition between bonded and unbonded material. The problem is conceptually analogous to a rigid patch terminating against weaker substrate: the edge becomes a location where deformation changes rapidly.

This reinforces the importance of avoiding unnecessary adhesive spread beyond the intended fracture. Squeeze-out is not simply a cosmetic nuisance. Uncontrolled polymer across weathered exterior marble can enlarge the permanently altered region and produce irregular stress boundaries.

6.10. Thick Adhesive Beds and the Transition to Structural Fills

At some point, an adhesive ceases to function predominantly as a bond line and begins to function as a structural fill. The distinction has no universal dimensional boundary, but it is conceptually important.

A thin resin layer connects two stone surfaces. A thick epoxy putty mass may instead bridge missing material, establish elevation, correct alignment, or support compressive load. Once those additional functions are assigned, the material must be evaluated not only for adhesion but also for creep, compressive deformation, shrinkage, stiffness, environmental response, and what happens if the fill itself must later be removed.

This is particularly relevant to Pratley Putty. Its mouldability is an advantage where isolated irregularities must be accommodated, but a large continuous Pratley bed would represent a very different treatment from several discrete restraint pads used alongside lead.

The same caution applies to heavily filled structural epoxies sold for stone fabrication or anchoring. Their ability to occupy large gaps can be technologically impressive while still making them less desirable for conservation where the void could be managed by a more compatible and replaceable bedding material.

6.11. Mechanical Interlock and Surface Texture

Adhesive joints do not rely exclusively upon molecular attraction. Rough and irregular stone surfaces allow cured resin to engage mechanically with microscopic depressions and projections. A natural fracture therefore provides a very different interface from a polished fabricated edge.

Commercial adhesives designed to bond polished stone demonstrate that substantial adhesion can be achieved even where mechanical roughness is limited. Tenax specifically markets Domo 10 as capable of bonding polished, damp, and dry surfaces. This is useful evidence of the adhesive's fabrication capability but should not be interpreted as a reason to seek comparable bond strength on every historic repair.

Natural fracture texture can allow strong adhesion without deliberately cutting, grinding, scoring, or roughening original marble. Preserving that texture also retains evidence of the original break and avoids additional material loss.

Where previous repairs have coated the fracture with incompatible resin or mortar, the situation becomes more difficult. Removal may improve new adhesion but can also destroy original fracture texture. The balance between preparation and preservation should therefore be determined case by case.

6.12. Dry-Fitting as Structural Diagnosis

Dry-fitting is often treated as a practical installation step, but it also provides valuable diagnostic information. Before adhesive is introduced, the practitioner can determine where the stone naturally bears, where gaps exist, whether fragments lock mechanically, whether previous deformation prevents accurate alignment, and which surfaces would actually transmit loads.

A tablet fracture that closes tightly without rocking may require very little adhesive volume. A multi-piece monument die that sits securely on three high points but leaves broad unsupported gaps presents a bearing problem that should be corrected before bonding. A

fragment that cannot be aligned without force may indicate missing material, deformation, or an incorrect reconstruction.

Dry-fitting therefore helps answer a critical conservation question: **What work is the adhesive being asked to perform that the stone itself cannot already perform?**

The smaller and more clearly defined that residual task becomes, the more controlled the treatment can be.

6.13. Joint Geometry and the Gravestone Guardians Model

The Gravestone Guardians repair approach examined in this paper relies heavily on geometry even when that geometry has not previously been described in formal terms.

For clean tablet fractures, the objective is intimate alignment and a thin structural adhesive joint. AKEPOX 5010 fills the fracture rather than creating a broad new structural layer.

For multi-piece monument reassembly, the objective is different. Stable compression and alignment are established with stone bearing and lead. Pratley Putty occupies selected three-dimensional locations where resistance to relative movement is desirable.

Monument setting compound closes the exposed joint without being required to carry the primary dead load.

These systems should therefore be evaluated separately. Measuring the tensile strength of AKEPOX and Pratley and declaring one safer than the other would miss the central mechanical distinction.

The relevant comparison is between **repair configurations**.

That conclusion provides the appropriate transition into the following material chapters. Structural adhesives must now be examined according to what their properties enable within those different geometries.

7. Structural Epoxy Adhesives

7.1. Why Epoxy Became Important in Stone Repair

Epoxy resins occupy an unusual position in conservation. They are among the most capable structural adhesives available for stone, yet their strength, permanence, and potential penetration into porous substrates are precisely the characteristics that have generated longstanding concern.

Two-component epoxy systems cure through chemical cross-linking rather than through evaporation of a carrier solvent. Once sufficiently cured, the resulting thermoset cannot ordinarily be returned to its uncured state by adding solvent. This distinguishes epoxy fundamentally from thermoplastic conservation adhesives such as Paraloid B-72.

The practical advantages are substantial. Epoxies can be formulated with low shrinkage, high adhesion, useful gap-filling capability, resistance to moisture and chemicals, controllable viscosity, and long-term dimensional stability. Different resin-hardener combinations produce very different working times, stiffnesses, optical characteristics, and environmental tolerances. Epoxy should therefore be treated as a broad material family rather than as a single material.

This variability is important to the paper's larger argument. The statement that “epoxy is too strong for marble” is no more technically complete than the statement that “epoxy is the strongest choice, therefore it is the best.” Individual formulations and joint configurations matter.

7.2. Thermosetting and Permanence

When epoxy resin and hardener react, a cross-linked molecular network develops. The process creates the mechanical and chemical durability for which epoxy is valued, but it also accounts for the difficulty of reversal.

Akepox 5010's current technical sheet states explicitly that hardened material can no longer be removed using solvents and instead requires mechanical removal or very high temperature. Those alternatives are rarely attractive on fragile historic marble. Mechanical removal risks loss of stone, while heating to temperatures capable of degrading epoxy would be inappropriate for most cemetery applications (AKEMI GmbH, 2022; see Appendix J).

This permanence should be accepted as a treatment fact rather than softened through language suggesting practical reversibility. If Akepox 5010 is used, the objective should be

to justify why permanent bonding is warranted and to limit the amount of historic surface placed into that irreversible condition.

The same general concern applies to HXTAL, Epo-Tek, Domo, Akepox, and other thermosetting systems, even though their precise chemical and mechanical properties differ.

7.3. Akepox 5010

Akepox 5010 provides the principal structural epoxy case study in this paper because it is the primary adhesive currently used by Gravestone Guardians for closely fitted tablet fractures.

AKEMI describes the product as a solvent-free, gel-like, two-component epoxy containing a cycloaliphatic polyamine hardener. The current technical data sheet identifies very low curing shrinkage, low tension in the bond layer, good weather resistance, good adhesion to slightly humid stone, relatively little yellowing, and the ability to form thin adhesive joints despite its gel consistency. The manufacturer lists bending strength of approximately 60–70 N/mm² and tensile strength of approximately 30–40 N/mm² under the referenced ISO test methods. Water absorption is reported below 0.5 percent, while Shore D hardness reaches approximately 83 after seven days under the listed curing conditions (AKEMI GmbH, 2022; see Appendix J). The same sheet cautions that bonding stability depends on the natural stone and states that silicate-bound stone responds better than carbonate-bound stone. Because marble is carbonate-bound, this manufacturer caveat reinforces the need for substrate-specific evaluation rather than reliance on nominal adhesive strength alone (AKEMI GmbH, 2022).

These values establish that 5010 is unquestionably a structural material. A tensile strength of 30–40 MPa should not be interpreted as a desired target for weathered marble; it describes the cured adhesive under the manufacturer's test conditions. Once bonded to historic stone, the actual repair may be limited by the marble, the interface, or fracture geometry long before the bulk polymer reaches that value.

The current sheet is also revealing for what it does not report. It does not provide a Young's modulus or tensile elastic modulus. Earlier secondary technical information has sometimes been used to compare the stiffness of 5010 with other epoxies, but where current manufacturer data do not provide a directly comparable value, this paper should avoid presenting such comparisons as settled fact. The absence itself illustrates one of the problems facing conservators: fabrication-oriented technical sheets do not always report the material properties most useful for conservation analysis.

7.4. Why 5010 Is Attractive for Tablet Fractures

Several characteristics of 5010 are favorable for closely fitting tablet repair even apart from ultimate strength.

Its gel consistency permits control on vertical surfaces and reduces uncontrolled flow compared with very low-viscosity resins. At the same time, AKEMI specifically notes that thin joints can be produced. Low curing shrinkage is desirable because polymerization contraction can introduce stress into a constrained fracture. Weather resistance and slight-damp tolerance are likewise relevant to cemetery work, where absolute laboratory dryness can be difficult to achieve even when the stone appears surface-dry (AKEMI GmbH, 2022).

The working time is also appropriate for deliberate alignment. At approximately 20°C, the technical sheet lists roughly 20–30 minutes of working time, with maximum stability reached after seven days. This is slow enough to permit careful placement without requiring the extremely extended cure associated with some conservation epoxies (AKEMI GmbH, 2022).

None of these advantages removes the conservation liabilities. The cured material is rigid, permanent, and strong enough to exceed the cohesive strength of some weathered marble. The case for 5010 therefore rests heavily upon **where and how it is used**: sound fracture substrate, accurate fit, minimum necessary adhesive volume, controlled squeeze-out, and avoidance of unnecessary widening or roughening of the historic break.

7.5. Akepox 5010 and Failure Hierarchy

If a 5010 repair survives a future impact while a new crack forms immediately beside the old fracture, the result must be interpreted carefully.

One possible conclusion is that the adhesive was too strong. Another is that the original fracture was successfully restored and the subsequent load exceeded the capacity of the next weakest section of marble. Both descriptions may be mechanically correct.

The conservation judgment depends on the magnitude and character of the event. A repair should not be expected to make a historic tablet indestructible. If a severe external impact would have broken unaltered marble elsewhere in the tablet, survival of the adhesive joint does not by itself condemn the treatment.

The concern becomes greater when normal environmental movement or modest loading repeatedly produces stone fracture adjacent to the bond. In that case, the repaired interface may be excessively rigid or strong relative to the surrounding substrate.

This distinction reinforces the need for long-term field monitoring rather than evaluation based solely on whether the glue remains intact.

7.6. Tenax Domo 10

Tenax Domo 10 provides an instructive contrast because it represents a formulation and marketing philosophy directed strongly toward permanent stone fabrication. Tenax describes Domo 10 as an extra-strong, two-component thixotropic epoxy for durable bonding of marble, stone, granite, ceramics, and engineered materials, including exterior and damp-surface applications (Tenax S.p.A., 2023; see Appendix J). The current U.S. product page goes further, stating that the stone will break before the adhesive fails (Tenax USA, n.d.-b).

From a fabrication perspective, this communicates confidence in bond performance. From a conservation perspective, it identifies the exact failure hierarchy that warrants scrutiny.

The current 2023 technical data sheet deserves closer attention because it is more nuanced than the marketing summary. Domo 10 is listed as a thixotropic paste mixed 1:1 by weight, with Shore D hardness of 62 following the specified post-cure. A peel test involving glass-fiber reinforcement on marble is reported at 1.5 N/mm. Numerical adhesion values for white marble are listed as unavailable in that sheet rather than as a specific high MPa value (Tenax S.p.A., 2023; see Appendix J).

The same technical sheet reports **high yellowing** in its Q-Sun climatic-chamber test representing one year of outdoor light, rain, darkness, and thermal shock exposure. This is particularly relevant to historic white marble. It does not mean Domo 10 lacks structural suitability outdoors—the manufacturer explicitly recommends it for exterior use—but it indicates that aesthetic aging may be more significant than the general exterior-use designation suggests (Tenax S.p.A., 2023).

For conservation, the distinction between structural durability and visual stability matters.

7.7. Domo 10 Versus Akepox 5010

It would be tempting to reduce the comparison between Domo 10 and Akepox 5010 to a ranking of bond strength, but currently available technical data do not support a clean direct comparison. The manufacturers report different properties under different test methods, and Tenax's current technical sheet does not supply a directly comparable marble tensile-bond figure.

More useful distinctions can nevertheless be drawn.

Akepox 5010 is explicitly characterized by low shrinkage, low bond-layer tension, very low yellowing tendency, and thin-joint capability. Its current sheet provides tensile and flexural strengths under ISO methods and identifies weather-resistant bonding of marble as a principal application (AKEMI GmbH, 2022).

Domo 10 emphasizes maximum adhesion, mixed-material bonding, wet-surface capability, and extreme exterior performance. Tenax's product literature describes it unapologetically as a permanent structural adhesive designed to remain stronger than the stone in many applications (Tenax S.p.A., 2023; Tenax USA, n.d.-b).

For new fabrication, Domo's performance philosophy is coherent. For fragile historic marble, the absence of any conservation advantage sufficient to offset its explicitly aggressive bond objective and documented yellowing concern makes it difficult to identify a compelling reason to replace 5010 with Domo 10 as Gravestone Guardians' routine tablet adhesive.

That conclusion is provisional rather than categorical. Direct testing on weathered marble could reveal advantages not apparent from the technical sheets. At present, however, Domo 10 is better treated as an important comparison material than as an obvious conservation upgrade.

7.8. Tenax Elix and Other Knife-Grade Epoxies

Tenax Elix illustrates a different direction within stone epoxies. It is marketed as an extra-clear two-component knife-grade epoxy for marble, granite, quartz, ceramic, and related materials, with low shrinkage, low yellowing, permanent adhesion, colorability, and both interior and exterior use (Tenax USA, n.d.-c; see Appendix J).

These characteristics make Elix more visually attractive for light stone than formulations in which yellowing is a greater concern. Yet the conservation analysis remains familiar: permanent cross-linked bonding, rigid cure, and limited retreatability.

Elix could reasonably enter a comparative testing program, particularly where visual appearance or a different working consistency is desired. At present, however, there is insufficient conservation-specific evidence to establish that it offers a meaningful preservation advantage over AKEPOX 5010.

This distinction is important throughout the paper. The existence of multiple technically capable products does not require a conservation organization to maintain an unnecessarily large adhesive inventory. Adoption should be driven by a demonstrated performance gap, not simply by product availability.

7.9. HXTAL NYL-1

HXTAL NYL-1 occupies a markedly different historical niche. It was developed specifically for conservation and restoration applications and is widely valued for optical clarity and resistance to yellowing, particularly in glass and ceramics (HXTAL Adhesive, LLC, n.d.; see Appendix J).

Its published technical data report tensile strength of approximately 5,400 psi, or about 37 MPa, tensile modulus of approximately 316,000 psi, or about 2.18 GPa, elongation of approximately 3 percent, and Shore D hardness near 78. The resin is low viscosity and cures much more slowly than many fabrication epoxies (HXTAL Adhesive, LLC, n.d.).

These numbers are revealing because HXTAL's conservation pedigree does not make it mechanically weak. Its reported tensile strength falls within roughly the same general range as AKEPOX 5010's published bulk tensile strength, although the data were generated under different conditions and should not be treated as a direct product ranking.

HXTAL therefore reinforces the argument established in Chapter 2: conservation compatibility does not correspond neatly with low tensile strength.

Its low viscosity can be beneficial where capillary penetration and very thin joints are desired, particularly in transparent materials. On weathered porous marble, the same characteristic raises questions about penetration into microcracks and the creation of an altered resin-rich zone. Its long cure and relatively low published heat-distortion temperature also deserve consideration for exterior cemetery exposure.

HXTAL remains highly significant to the literature review, but there is presently little reason to regard it as a superior routine outdoor monument adhesive merely because it originated within conservation practice.

7.10. Epo-Tek 301-2

Epo-Tek 301-2 is another low-viscosity optical epoxy encountered in conservation research. The current technical sheet describes a two-component, clear, pourable epoxy with an approximately eight-hour pot life and a recommended elevated-temperature cure, while a 48-hour cure at 23°C is listed as an alternative that may not produce the full published performance properties. Storage modulus is reported at approximately 432,279 psi, roughly 3.0 GPa, and lap shear exceeds 2,000 psi under the manufacturer's stated conditions (Epoxy Technology, Inc., n.d.; see Appendix J).

Jorjani and colleagues included Epo-Tek 301-2 in their marble fracture-toughness study, making it more directly relevant to conservation than many industrial epoxies (Jorjani et al., 2008).

Nevertheless, the product was not developed specifically for exposed cemetery marble. Its low viscosity and very long working period may be useful for specialized repairs but unnecessary for straightforward tablet fractures. As with HXTAL, conservation use should be based upon the requirements of the joint rather than upon the assumption that a laboratory or museum adhesive is automatically preferable outdoors.

7.11. Akepox 2000

Akepox 2000 also appears in the conservation literature and provides another useful comparison within the AKEMI family. It is a liquid, solvent-free epoxy formulated for very low curing shrinkage, weather-resistant bonding, dimensional stability, and adhesion to slightly humid stone (AKEMI GmbH, n.d.-a; see Appendix J).

Its liquid consistency differentiates it from the gel-like 5010. That lower viscosity may improve wetting and penetration but can make control on vertical tablet fractures more difficult and may increase penetration into porous or microcracked stone.

Jorjani's inclusion of Akepox 2000 demonstrates that commercial stone epoxies can be examined within a conservation research framework rather than being dismissed categorically because of their industrial origin.

For Gravestone Guardians, however, 5010's controllable gel consistency appears better matched to the practical geometry of tablet breaks unless a particular repair requires substantially lower viscosity.

7.12. Epoxy Penetration and Surface Consolidation

One advantage of low-viscosity epoxy can become a conservation liability when the substrate is weakened. Resin entering pores and microcracks may improve local cohesion, effectively producing a narrow region of consolidation adjacent to the fracture. This can strengthen an otherwise unreliable bond surface.

The same process reduces retreatability and changes the failure boundary. Instead of a clear interface between marble and polymer, the repair may develop a gradient from resin-rich stone to untreated stone. Future fracture can migrate to the outer edge of that altered region.

This effect is likely to vary greatly among marbles. Dense, relatively sound crystalline surfaces may absorb very little resin, while severely microcracked or sugared stone can permit deeper penetration.

For this reason, exceptionally low viscosity should not automatically be treated as an adhesive advantage in historic marble. The desired viscosity is the one that wets the intended interface adequately while allowing reasonable control over the extent of polymer penetration.

7.13. Epoxy Stiffness and Temperature

Epoxies are frequently described simply as rigid, but their stiffness changes with formulation, cure state, temperature, moisture, and aging. This becomes especially important near the material's glass-transition region, where mechanical behavior can change substantially.

Research evaluating epoxies used in conservation has demonstrated that curing and subsequent thermal aging can shift glass-transition behavior as cross-linking continues. HXTAL NYL-1, Fynebond, and Araldite 2020 all showed changes following artificial aging in one recent study of adhesives for outdoor architectural tile fragments (Musacchi et al., 2024).

For cemetery repair, the implication is not that these materials necessarily become unsafe at summer temperatures. It is that polymer properties measured at standard laboratory temperature are not immutable constants. Exterior joints experience seasonal conditions under which the adhesive, marble, and setting materials may respond differently.

Long-term environmental testing should therefore include mechanical evaluation after aging rather than simply confirming that the adhesive remains visibly intact.

7.14. Epoxy Shrinkage

Curing shrinkage is often overlooked because epoxy generally shrinks less than many polyester systems. Even small contraction, however, can be relevant in a rigidly constrained stone joint.

AKEPOX 5010's low-shrinkage formulation is therefore a genuine advantage. AKEMI specifically links its very low shrinkage to reduced tension within the bonding layer. Akepox 2000 makes similar claims (AKEMI GmbH, 2022, n.d.-a).

The importance of shrinkage increases with adhesive volume. A thin fracture contains relatively little resin and therefore relatively little absolute dimensional change. A thick fill or broad bedding layer contains more material and can generate larger cumulative effects.

This again demonstrates why material and geometry cannot be separated.

7.15. Moisture Tolerance Is Not Moisture Indifference

Several modern stone epoxies advertise adhesion to damp stone. AKEPOX 5010 lists good adhesion to slightly humid stone, while Domo 10 is promoted for wet or damp substrates (AKEMI GmbH, 2022; Tenax S.p.A., 2023).

These statements are useful but should not be interpreted as evidence that moisture condition no longer matters.

A substrate can be sufficiently damp for an adhesive to cure yet still suffer from ongoing moisture movement, salts, freeze-thaw activity, or biological growth. The question of whether epoxy will adhere today is different from whether the repaired joint will interact favorably with that moisture regime over decades.

Whenever practical, stone should therefore be allowed to reach a reasonably dry and stable condition before structural bonding, even when the selected adhesive possesses damp-surface tolerance. Moisture tolerance should function as resilience against field variability rather than as a substitute for substrate diagnosis.

7.16. Epoxy and Exterior Appearance

Aesthetic stability has structural significance because discoloration frequently prompts unnecessary retreatment. A mechanically sound joint that turns dark yellow against white marble may be considered visually unacceptable and could encourage later grinding, cutting, or replacement.

AKEPOX 5010 is specifically formulated to minimize yellowing relative to conventional epoxy systems, although its manufacturer notes that persistent, elevated temperatures can increase discoloration. HXTAL likewise emphasizes long-term optical stability (AKEMI GmbH, 2022; HXTAL Adhesive, LLC, n.d.).

Domo 10 presents a notable contrast because its 2023 technical sheet assigns a high yellowing result after the listed simulated outdoor exposure (Tenax S.p.A., 2023).

This does not alone determine structural suitability, but it strengthens the argument that epoxies should not be considered interchangeable on light historic marble.

7.17. Comparative Assessment of Selected Structural Epoxies

Adhesive	Relevant strengths	Principal limitations for exterior historic marble	Preliminary role

Adhesive	Relevant strengths	Principal limitations for exterior historic marble	Preliminary role
Akepox 5010	Low shrinkage; weather resistant; gel consistency; thin joints possible; slight-damp tolerance; low yellowing tendency; published tensile strength 30–40 MPa	Permanent; rigid; no solvent reversal after cure; can exceed cohesive strength of weathered marble	Primary candidate for sound, closely fitting tablet fractures
Tenax Domo 10	Strong permanent bonding; thixotropic; exterior rated; damp-surface capability; broad material adhesion	Explicit substrate-breaking performance objective; current TDS reports high simulated-outdoor yellowing; limited directly comparable marble mechanical data	Useful comparison; difficult to justify as routine replacement for 5010
Tenax Elix	Low shrinkage; low yellowing; clear; exterior capable; knife-grade handling	Permanent rigid thermoset; limited conservation-specific testing	Possible alternative where visual requirements favor it
HXTAL NYL-1	Conservation pedigree; clarity; low yellowing; known modulus and elongation; extensive museum use	Very low viscosity; long cure; permanent; limited exterior-monument evidence; possible deeper penetration	Important conservation benchmark; specialized rather than default cemetery adhesive
Epo-Tek 301-2	Low viscosity; long working time; documented conservation testing	Permanent; specialized cure requirements; not formulated specifically for exterior stone	Research and specialized-treatment candidate
Akepox 2000	Low shrinkage; weather resistance; low viscosity; included in marble conservation research	Greater flow and penetration than 5010; permanent	Useful low-viscosity comparison

The table should not be read as a ranking from safest to most dangerous. The significance of each property depends upon substrate and joint design.

7.18. Conservation Position on Structural Epoxies

The literature and manufacturer data support neither categorical rejection nor uncritical acceptance of structural epoxy for historic marble.

Epoxy provides capabilities that may be difficult to achieve with mineral or thermoplastic alternatives, particularly where a narrow fracture must recover substantial tensile and bending continuity. The same material becomes less compelling where broad bearing and gravity already supply the majority of structural support.

For Gravestone Guardians, continued use of AKEPOX 5010 for appropriate tablet fractures remains defensible as a working practice provided the limitations are stated clearly. The material should not be described as reversible, should not be used to compensate for severely deteriorated substrate, and should not be applied more broadly than required.

Its appropriateness depends not upon epoxy being harmless, but upon the alternative interventions being considered honestly.

A narrow permanent bond across an existing fracture may in some cases preserve more original material than drilling multiple holes for rigid reinforcement. In other cases, deteriorated stone or high structural demand may make that adhesive-only solution inadequate.

That is precisely the type of object-specific judgment this paper seeks to formalize.

8. Epoxy Putties and Gap-Filling Adhesives

8.1. A Different Form of Epoxy Intervention

Epoxy putties are frequently grouped with liquid and gel structural epoxies because their underlying chemistry is related. Mechanically, however, their typical use is different enough to justify separate treatment.

A putty is designed to remain where it is placed, occupy three-dimensional space, bridge irregularities, and often permit hand shaping before cure. It can therefore perform simultaneously as adhesive, gap filler, restraint, and in some cases bearing medium.

These advantages make putties extremely useful in practical monument work. They also make overuse easy.

Where a thin epoxy joint may introduce only a small volume of polymer, a putty can become a substantial structural element. The conservation question is therefore not simply whether the material bonds to marble. It is how much polymer is introduced, what load the cured mass carries, and how readily the assembly can be separated in the future.

8.2. Pratley Standard Setting Putty

Pratley Standard Setting Putty is the principal case study because it occupies a defined role within current Gravestone Guardians multi-piece monument reassembly.

The manufacturer describes the product as a two-component, hand-mouldable, high-performance adhesive that sets very hard and adheres to stone, cement, concrete, glass, slate, wood, metal, and other rigid materials. It can be used underwater and is specifically formulated for filling, sealing, building up, and bonding rigid materials (Pratley, 2023; see Appendix J).

The current instruction leaflet lists a gel time of approximately 50 minutes at room temperature, hard set after roughly four hours, and full strength after approximately 24 hours, subject to temperature and quantity. It can be shaped with a wet tool before cure and machined after hardening (Pratley, 2023).

These working characteristics help explain its value during monument setting. It provides considerably more placement control than a flowing epoxy and allows an installer to create discrete pads or small three-dimensional restraints without the material running across the interface.

8.3. The Significant Gap in Published Pratley Data

Pratley's public product information is useful operationally but comparatively limited from a conservation-science perspective. The manufacturer emphasizes high adhesive performance and hard cure but does not provide, in the currently reviewed public materials, the complete tensile modulus, fracture toughness, thermal-expansion, creep, or marble-specific bond data needed for rigorous comparison with other systems (Pratley, 2023).

That absence should be treated as an evidence gap rather than filled through assumption.

It would be inappropriate to declare Pratley “softer than epoxy,” “weaker than marble,” or more flexible than AKEPOX 5010 without data supporting those conclusions. The material is itself an epoxy-based hard-setting adhesive, and its conservation justification should not depend upon portraying it as mechanically weak.

The stronger argument is geometric: **Gravestone Guardians uses Pratley in a deliberately limited structural role.**

That claim can be tested experimentally even if complete manufacturer mechanical data remain unavailable.

8.4. Pratley as Localized Restraint

In the GG system, Pratley Standard Setting Putty is not intended to form a continuous horizontal adhesive laminate beneath the monument component. The upper stone is dry-fitted and placed into stable bearing using the stone interface and wedge lead. Small quantities of Pratley are then positioned to resist relative movement, while monument setting compound is used at the exposed joint. This arrangement matters mechanically.

The Pratley does not need to carry the entire vertical dead load. Nor does it need to create a bond across every square inch of the historic interface. Its principal task is supplemental restraint.

If that intent is maintained during application, the system potentially limits both the amount of original stone exposed to permanent adhesive and the total area through which the polymer can transmit tension or shear.

The distinction should be documented because the same product used continuously could create a much more invasive treatment.

8.5. The Danger of Turning Pads into a Bedding Layer

One practical risk with any mouldable putty is gradual expansion of its role. Several small pads can easily become larger pads; larger pads can become broad bands; eventually most of the horizontal interface may be occupied by cured polymer.

At that point the system is no longer meaningfully “limited bond.” The putty has become a structural bedding material.

That change has consequences. A large mass of rigid polymer can carry vertical compression, restrain differential movement, complicate dismantling, and produce localized load transfer into the marble. If the stone is not actually bearing independently, subsequent creep or deformation of the putty may also influence alignment.

A Gravestone Guardians treatment specification should therefore eventually define limited-bond reassembly not merely by product choice but by observable design criteria: stable independent bearing, adhesive placed away from fragile edges, no continuous perimeter band of structural putty, and no use of putty to compensate for fundamentally defective support.

The appropriate quantitative limits remain to be established experimentally.

8.6. Pad Placement

The safest location for adhesive restraint is not necessarily the most accessible location.

Putting pads directly at the outside edge facilitates placement but also positions the rigid bond where peel and overturning stresses may be greatest and where the marble is frequently thinnest or most weathered. Edge placement can also interfere with later removal of perimeter setting compound.

Interior placement offers potential advantages because more stone surrounds the bonded region. Yet placing adhesive too deeply can make future access extremely difficult.

The ideal location is therefore a compromise among structural effectiveness, substrate soundness, and retreatability.

A reasonable working principle is to keep structural putty away from highly deteriorated edges and to avoid placing it where a future break would threaten carved detail, inscription, or thin projections. Exact pad placement should be documented photographically before the upper component is lowered into its final position.

8.7. Pad Thickness and Bearing

Pratley Putty can conform to irregularities, but that capability should not lead to a repair in which the monument is intentionally floated on thick adhesive pads.

If vertical load is concentrated primarily through Pratley, the material is acting as a bearing system. The resulting performance becomes dependent upon long-term compressive behavior and creep characteristics that are not sufficiently characterized in the conservation literature for this application.

Lead and sound stone bearing provide a more legible load path. The role of Pratley can then remain primarily lateral and tensile restraint.

Small incidental compression through the adhesive is unlikely to be completely avoidable. The relevant distinction is whether the monument would remain properly supported if the adhesive pads suddenly lost their structural capacity.

That question provides a useful field test of the limited-bond philosophy:

If removing the putty would cause the upper stone to drop, tilt, or lose stable bearing, the putty is doing more than restraint.

8.8. Pratley Standard Versus Pratley Quickset

Pratley Quickset Putty is marketed as similar to the Standard Setting formulation but with a faster cure and exceptionally high strength (Pratley, n.d.-b).

Faster cure can be attractive in field work because it reduces the time components must remain restrained. For careful monument reassembly, however, speed is not necessarily an advantage. Longer working time allows the setter to verify level, plumb, bearing, alignment, and final joint width before cure advances significantly.

The slower Standard Setting formulation therefore appears better aligned with preservation work where deliberate adjustment is more important than production speed.

Unless field conditions create a compelling need for rapid set, Quickset offers little obvious conservation advantage.

8.9. Pratley Industrial Putty

Pratley states that its Industrial Putty is compositionally identical to Pratley Putty Standard Setting, differing primarily in package size and available color (Pratley, n.d.-a).

This is useful operationally because larger conservation projects may require quantities impractical to obtain in small consumer packages. From a technical perspective, however,

the same limitations and advantages apply. Larger packaging does not make the material more appropriate for larger adhesive beds.

If adopted for monument work, it should remain subject to the same limited-area philosophy.

8.10. Tougher and More Flexible Resin Systems

The discussion of failure hierarchy naturally raises the possibility of using adhesives that retain high bond strength while deforming more than conventional rigid putties.

Pratley Wondafix is an interesting example. The manufacturer describes it as a tough but flexible adhesive that cures to a hard but flexible rubber and is designed for shock-resistant bonding. It adheres to stone among numerous other materials (Pratley, n.d.-c).

Conceptually, such a material could reduce peak stresses by accommodating movement that a hard epoxy putty would resist. Yet flexibility alone does not establish conservation suitability. Greater deformation can introduce creep under sustained load; softer polymers may trap dirt, age differently outdoors, or permit movements that gradually destabilize alignment. Published long-term performance data on weathered historic marble are insufficient.

Wondafix therefore belongs in the experimental program, not yet in the standard field protocol.

Its importance lies in broadening the question beyond the simplistic choice between very hard epoxy and weak reversible resin. Tough, moderately deformable structural polymers may ultimately occupy a useful middle range if durability and failure behavior prove favorable.

8.11. Milliput and General-Purpose Epoxy Putties

Milliput is another well-known two-component epoxy putty. The manufacturer describes it as non-shrinking, self-hardening, durable, water resistant, capable of setting underwater, and adhesive to masonry, ceramics, glass, metals, wood, and other materials (Milliput, n.d.).

These characteristics make Milliput useful for modeling, fills, ceramics, sculpture, and small repairs, but they do not establish it as a preferred structural adhesive for large exterior marble monuments. Publicly available technical information is oriented more toward general repair and modeling than toward quantified structural stone performance.

For this paper, Milliput is best considered representative of a broad class of commercially available epoxy putties whose practical workability can make them attractive to restorers even when their long-term conservation performance is poorly characterized.

The lesson is not that these materials are necessarily inferior. It is that **workability should not substitute for evidence**.

8.12. Filled Epoxy Systems and Mechanical Behavior

Epoxy putties differ from unfilled liquid resins partly because fillers modify viscosity, shrinkage, density, workability, and mechanical properties. Mineral or other particulate additions can transform a flowing resin into a mouldable mass and may reduce the amount of polymer required to occupy a given volume.

The resulting composite, however, does not necessarily become more compatible with marble merely because it contains mineral filler. The polymer matrix still governs much of the bond behavior and remains essentially irreversible after cure.

Fillers may increase stiffness, alter fracture behavior, reduce shrinkage, or change thermal expansion depending upon their type and concentration. Without formulation-specific data, these effects cannot be assumed.

This is another reason product categories should not be reduced to labels such as “epoxy putty.” Two putties can share a general chemistry while behaving very differently.

8.13. Gap Filling Versus Loss Compensation

A distinction should be maintained between filling a structural gap and replacing visible missing historic material.

A structural gap exists within the load path between components. The fill may influence bearing, stress transfer, and stability.

Loss compensation, by contrast, may principally restore a missing edge, surface, or visual contour. Such material may not need high structural strength and can often be selected for compatibility, appearance, and future removal rather than maximum adhesion.

Using Pratley Putty or similar hard epoxy to replace every visible loss merely because the material can be shaped is therefore difficult to justify. Mineral repair mortars, lime-based fills, or other restoration materials may provide a more appropriate sacrificial relationship for exposed losses.

Epoxy putty should be reserved for roles that genuinely benefit from its structural properties.

8.14. Putty and Moisture

Pratley promotes Standard Setting Putty for underwater use, demonstrating that cure and adhesion are not dependent upon a completely dry environment (Pratley, 2023).

As with damp-tolerant epoxies, this capability should be interpreted carefully. It improves resilience during installation but does not answer questions about long-term moisture behavior within a cemetery monument.

A relatively impermeable putty pad can locally interrupt moisture pathways. In a limited-bond configuration, this altered area is small relative to the entire joint. In a continuous putty bed, the moisture consequences could be much greater.

This provides another conservation argument for limiting adhesive area even when mechanical strength alone would permit more extensive use.

8.15. Putty and Retreatability

Epoxy putty should be regarded as essentially permanent once bonded to marble. Its mouldable application can, however, provide a degree of **geometric retreatability** if used in discrete locations.

A future conservator may be able to remove perimeter setting material, identify the general location of the pads from treatment records, introduce controlled mechanical separation between them, and eventually remove residual putty from accessible areas. None of those steps is guaranteed to be easy or harmless, but they are more plausible than separating two broad surfaces bonded continuously with epoxy.

This is one of the most important distinctions in the entire paper. Permanence is chemical; retreatability is architectural.

A limited number of permanent adhesive points can coexist with a substantially retreatable assembly if the joint remains understandable and accessible.

The validity of this proposition should be tested rather than asserted, but it provides a coherent explanation for why localized Pratley may offer a reasonable middle position between no restraint and full permanent bonding.

8.16. Comparing Pratley with Pinning

Pratley and pinning solve different structural problems but may sometimes compete for the same treatment decision.

A pin provides positive mechanical restraint across an interface and can offer predictable resistance to sliding, uplift, or bending when properly designed. It requires drilling original stone and concentrates load around the anchorage.

Localized putty avoids drilling but places permanent polymer directly on the historic interface. Its total structural capacity may be lower and less predictable without detailed testing, but the intervention can be distributed over broader surface areas without removing stone.

For relatively low, broad monument sections that already possess substantial gravitational stability, limited adhesive restraint may therefore be less invasive than introducing pins primarily as insurance against movement.

For tall, narrow, or safety-critical components, pins may provide capacity that limited putty cannot reliably replace.

The choice should therefore remain structural rather than ideological.

8.17. Assessment of Epoxy Putty Systems

The evidence available at present supports a cautiously favorable view of Pratley Standard Setting Putty **within a narrowly defined limited-bond system**, but not as a general substitute for conservation-compatible bedding or mortar.

Its principal advantages are workability, gap accommodation, slow enough cure for adjustment, strong adhesion to rigid mineral materials, and the ability to remain where placed. Its principal disadvantages are permanence, hard cure, incomplete publicly available mechanical characterization, and the potential for overuse.

Gravestone Guardians' practice is most defensible when the putty remains visibly subordinate to the bearing system.

That principle should eventually be incorporated into treatment documentation:

Pratley Putty is used to restrain the assembly, not to create the assembly.

If experimental testing supports that distinction, it could represent one of the most useful practical contributions of this paper.

9. Polyester and Stone-Fabrication Mastics

9.1. The Historical Importance of Polyester Adhesives

Polyester resins have a long history in stone fabrication and conservation. Introduced commercially during the twentieth century, they became attractive because they cure rapidly, can be thickened or filled, polish readily, accept pigments, and provide strong adhesion to many stone surfaces.

The conservation literature records their use as adhesives, fills, and consolidants for stone. Jorjani and colleagues included Marmorkitt 1000 in their comparative marble study, noting both the established history of polyester use and the continued polymerization shrinkage associated with polyester curing (Jorjani et al., 2008).

Polyester mastics therefore cannot simply be dismissed as inappropriate commercial products that exist outside conservation history. They have been used by both fabricators and conservators.

The relevant question is whether their advantages remain compelling for exterior historic marble now that more weather-resistant, lower-shrinkage epoxy systems are widely available.

9.2. How Polyester Stone Mastics Differ from Epoxy

Although polyester mastics and epoxies may look similar in the workshop, their curing chemistry and practical behavior differ.

Polyester stone adhesives are typically supplied as a resin or mastic to which a relatively small amount of initiator or hardener is added. Cure can be very rapid. This allows stone fabricators to fill, seam, polish, and continue production quickly.

Epoxies generally require more precise stoichiometric mixing of two substantial components and often cure more slowly. In return, they typically offer lower shrinkage and better moisture and exterior durability.

Tenax itself summarizes the practical distinction by recommending polyester primarily for interior seaming, color-matched repairs, and production work, while identifying epoxy as preferable for exterior, wet, and structural applications (Tenax USA, n.d.-e).

That industry guidance aligns surprisingly well with the conservation concerns relevant to cemetery marble.

9.3. Speed as Both Advantage and Limitation

Rapid cure is one of polyester's greatest commercial advantages. Tenax Tixo XE, for example, is marketed with only a few minutes of working time and curing within approximately 12–15 minutes (Tenax USA, n.d.-g).

Such speed is valuable in a fabrication shop where pieces are accurately machined and production efficiency matters.

Historic monument reassembly benefits from a different tempo. Irregular surfaces must be dry-fitted, components may require gradual hoist adjustment, lead wedges must be set, alignment checked from multiple directions, squeeze-out controlled, and fragile stone monitored throughout the operation.

An adhesive beginning to gel after only several minutes reduces the margin for careful correction. It also encourages rushed mixing and placement—two workmanship problems that can matter more than theoretical differences in resin strength.

For conservation field work, additional working time is frequently an advantage rather than an inefficiency.

9.4. Polymerization Shrinkage

Polyester curing involves measurable shrinkage. Jorjani's review notes that shrinkage associated with polymerization may continue beyond the initial gel and cure period.

Catalyst proportion remains a workmanship variable that should stay within manufacturer limits rather than being increased casually to accelerate cure. Current Tenax polyester instructions specify controlled resin-to-catalyst ratios and immediate application after mixing (Tenax USA, n.d.-a, n.d.-g).

Shrinkage becomes particularly relevant in thick fills or broad joints, where a larger volume of resin undergoes dimensional change. In a rigid marble assembly, contraction can introduce tension into the bond or produce small gaps and stress concentrations.

Modern formulations may control this behavior effectively enough for fabrication, but the availability of low-shrinkage epoxies reduces the incentive to accept greater polymerization contraction in historic exterior marble when no other polyester property is uniquely required.

9.5. Interior Versus Exterior Use

The exterior limitation of many polyester mastics is unusually clear in current manufacturer literature.

Tenax Colored Knife Grade Polyester is specifically recommended for interior use only and is not recommended below 32°F. Tenax Solido XQ is likewise recommended for interior use and excluded below freezing. Tixo XE is described as an interior product despite its strong bond and resistance to water, oils, and chemicals (Tenax USA, n.d.-a, n.d.-f, n.d.-g).

AKEMI's current Marmorkitt 1000 information similarly identifies the product as an interior, rigid polyester adhesive with low UV stability (AKEMI GmbH, n.d.-b).

These limitations are difficult to reconcile with routine use on historic cemetery monuments in climates experiencing freezing temperatures, direct sunlight, precipitation, and wide seasonal temperature swings.

A product can bond marble very strongly and still be a poor exterior conservation choice.

9.6. UV Stability and Yellowing

Color stability is especially important on white and light-gray marble because even modest resin discoloration can become visually prominent.

AKEMI explicitly rates the UV stability of Marmorkitt 1000 Universal as low. Tenax formulations vary, but many conventional polyester products are marketed primarily for interior seams and repairs where UV exposure is limited (AKEMI GmbH, n.d.-b).

Polyester mastics are often extremely easy to color and polish, making them cosmetically excellent when first installed. That initial visual success can obscure longer-term aging concerns.

Historic monument repair should prioritize how the repair will appear after years of sunlight and moisture rather than merely how accurately it can be polished on the day of treatment.

This is one area in which a slower, less convenient exterior epoxy may represent a better preservation tradeoff.

9.7. Marmorkitt 1000

Marmorkitt 1000 is particularly important because it appears directly in conservation research and has a long history in the stone industry.

AKEMI currently offers multiple Marmorkitt formulations for bonding, filling, modeling edges, and repairing natural stone. Current product information describes the conventional Universal and S formulations as rigid polyester systems intended primarily for interior use, with low UV stability and rapid curing (AKEMI GmbH, n.d.-b).

Jorjani and colleagues nevertheless found Marmorkitt sufficiently relevant to include among eight marble adhesive systems in their interfacial fracture-toughness study.

This combination of evidence is instructive. Marmorkitt can be mechanically capable of joining marble while simultaneously possessing environmental characteristics that make it less attractive for exterior cemetery use.

Strength and suitability diverge once again.

9.8. Low-Viscosity Polyester as a Surface Treatment

Some polyester systems are sufficiently fluid to penetrate porous stone and have historically been promoted as primers, consolidating resins, or filling materials. AKEMI's extra-thin Marmorkitt 1000, for example, is marketed for pretreatment of porous or sandy marble and limestone as well as for bonding letters and modifying other polyester adhesives (AKEMI GmbH, n.d.-b).

From a conservation standpoint, this use deserves considerable caution. Penetrating a weak stone surface with irreversible polyester creates a much larger altered zone than simply joining a clean fracture. The resulting consolidation may improve immediate cohesion but complicates moisture behavior, color, retreatability, and future failure.

This paper does not evaluate polyester consolidation comprehensively, but its existence reinforces an important principle: an adhesive's ability to penetrate weak stone should not be confused with evidence that the treatment is compatible with that stone.

9.9. Polyester Brittleness and Failure

Cured polyester mastics are generally rigid structural materials. Their practical advantage lies in rapid hardening and polishability rather than in accommodating substantial movement.

In marble repair, this rigidity can contribute to substrate failure when the bond itself remains intact. Podany's earlier marble research and Jorjani's later studies demonstrate that polyester adhesives can produce joints with substantial mechanical capacity (Podany et al., 2001; Jorjani et al., 2008).

That performance may be entirely appropriate for fabricated stone. For weathered marble, however, it offers no inherent advantage over structural epoxy if both systems are capable of exceeding the stone's cohesive strength.

The selection then turns to secondary properties: shrinkage, exterior durability, working time, UV behavior, moisture tolerance, and retreatability.

On most of those criteria, high-quality exterior epoxies appear better matched to cemetery use.

9.10. Polyester as Fill Rather Than Structural Adhesive

One area in which polyester remains attractive commercially is cosmetic filling. It accepts color readily, cures quickly, can often be sanded and polished, and is available in multiple viscosities.

For historic exterior marble, mineral repair materials may often provide a more compatible option for visible losses because they can be formulated closer to the appearance, porosity, and sacrificial behavior of the stone.

A rigid polyester fill in a weathered edge can remain stronger than the surrounding marble and eventually contribute to edge breakout. It may also yellow differently from the mineral substrate.

The ability to polish a fill until it nearly disappears should not be mistaken for conservation compatibility.

Where polyester is encountered as an existing historic repair, the decision to retain or remove it should depend upon its condition and consequences rather than its chemistry alone. A stable old repair that is causing no apparent damage may not warrant destructive removal merely because the material would not be selected today.

9.11. Polyester in the Monument Industry

The continued prevalence of polyester mastics in monument and stone fabrication is understandable. They are inexpensive compared with many specialty epoxies, easy to tint, fast, polishable, and familiar to generations of stone workers. Those advantages solve real production problems.

Cemetery preservation differs because labor efficiency is not the only relevant measure. An additional hour of cure time may be inconsequential compared with decades of exterior exposure. A repair that cannot be polished immediately may still be preferable if it ages more predictably and transfers less curing stress.

This is an important point because “industry standard” is frequently invoked in debates over monument repair. The existence of a standard fabrication practice demonstrates that a material works within that industry; it does not establish that its performance criteria match conservation objectives.

Conversely, conservators should not disregard monument-industry experience. Products that have failed repeatedly outdoors are often identified first by fabricators and setters. Current manufacturer guidance steering outdoor work toward epoxy rather than conventional polyester reflects that accumulated practical distinction.

9.12. Vinyl Ester as an Intermediate Category

Vinyl ester adhesives occupy an intermediate position between conventional polyester and epoxy and deserve brief consideration even though they are not the principal focus of this chapter.

Manufacturers market vinyl esters as offering faster cure than many epoxies while improving chemical and environmental resistance relative to polyester. Tenax, for example, presents vinyl ester as a middle-ground option when more durability than polyester is desired without accepting the full working time of epoxy (Tenax USA, n.d.-d, n.d.-e).

This raises an interesting research question for historic stone. A vinyl ester with favorable outdoor aging, moderate shrinkage, controlled stiffness, and sufficient rather than excessive bond strength might theoretically occupy useful territory between conventional polyester mastics and slow structural epoxies.

At present, however, conservation-specific marble evidence is too limited to recommend such systems routinely.

They should be included in future screening only where their properties suggest a genuine advantage over the materials already available.

9.13. When Polyester Might Still Be Reasonable

A categorical prohibition on polyester would be difficult to defend because applications vary and specialized formulations continue to evolve.

Possible situations could include small sheltered repairs on comparatively sound stone, temporary shop work on replacement components, indoor mausoleum elements, or restoration of previous polyester work where matching material behavior is important. Those situations differ substantially from exposed nineteenth-century cemetery marble.

For routine exterior structural fracture repair, the central question is whether polyester offers an advantage sufficient to justify accepting faster cure, greater shrinkage concern, and frequently inferior manufacturer-rated UV or outdoor performance.

In most circumstances examined here, it does not.

9.14. Conservation Implications for Polyester Mastics

Polyester mastics have demonstrated their ability to bond and fill marble effectively. That is not in dispute. Their limitations emerge when immediate fabrication performance is separated from long-term exterior conservation performance.

For Gravestone Guardians, there presently appears to be little reason to introduce conventional polyester mastics as a primary structural adhesive when AKEPOX 5010 already provides a slower-curing, low-shrinkage, weather-resistant epoxy system designed for marble and exterior use (AKEMI GmbH, 2022; Tenax USA, n.d.-e).

Likewise, Pratley Standard Setting Putty provides a more controllable material for the localized three-dimensional restraint role currently envisioned in multi-piece monument reassembly (Pratley, 2023).

Polyester therefore occupies a comparatively narrow position in the proposed treatment framework. It is technically capable but usually **not preferred** for exposed historic marble where better-characterized exterior alternatives are available.

That conclusion is not based on the assertion that polyester is “too strong.” Some formulations may be no stronger than the epoxies considered elsewhere. The limitation is the combination of material properties: rapid working time, polymerization shrinkage, rigid cure, permanence, and the restricted exterior or UV recommendations attached to many commonly available products.

The distinction is important because it demonstrates the decision framework working as intended. Adhesive selection does not depend upon identifying one property that automatically disqualifies a material. It depends upon determining whether the total balance of properties creates an advantage for the particular historic monument.

For conventional polyester mastics used outdoors on weathered marble, that balance is presently difficult to establish.

10. Acrylic and Thermoplastic Adhesives

10.1. The Conservation Appeal of Thermoplastic Adhesives

The discussion of structural adhesives in historic stone conservation frequently becomes polarized between permanent high-strength thermosetting resins and comparatively weak traditional materials. Thermoplastic acrylic adhesives complicate that division because they can provide substantial structural capacity while retaining an important characteristic generally absent from cured epoxy and polyester systems: they do not form the same permanently cross-linked molecular network and can remain soluble in appropriate solvents after curing.

Paraloid B-72 is the best-known example. Its widespread adoption in conservation arises from a combination of long-term chemical stability, optical clarity, comparatively low yellowing, broad solvent compatibility, and the ability to function as a coating, consolidant, and adhesive. Dow continues to describe B-72 as a thermoplastic acrylic resin forming clear, flexible films, while conservation literature has documented its use for decades across numerous object classes (Dow, n.d.-b; Podany et al., 2001).

That history creates an understandable temptation to regard B-72 as inherently more compatible with historic marble than epoxy. Chemically and ethically, its continued solubility offers a significant advantage. Mechanically, however, the distinction is less simple. Experimental work on marble demonstrates that concentrated B-72 formulations can produce joints sufficiently strong that the marble itself fails before the adhesive interface.

B-72 therefore provides an important test of the central thesis of this paper. An adhesive can be highly regarded within conservation, substantially more retreatable than epoxy, and still produce a failure hierarchy in which original stone becomes the weakest component.

The value of thermoplastic adhesives lies not in guaranteeing a weak joint, but in potentially preserving more options for future intervention.

10.2. Thermoplastic Versus Thermosetting Behavior

The distinction between thermoplastic and thermosetting adhesives is fundamental to understanding their conservation behavior.

A thermosetting epoxy develops a chemically cross-linked network during cure. Once that network has formed, conventional solvents may swell or degrade the resin but cannot simply return it to its original liquid state. Removal generally requires mechanical action, aggressive chemical exposure, substantial heating, or some combination of these.

A thermoplastic acrylic behaves differently. The polymer chains are not permanently joined into the same type of cross-linked network. Appropriate solvents can soften or dissolve the resin after application, permitting at least some degree of future removal.

This difference does not mean that a thermoplastic treatment is completely reversible. If dissolved acrylic penetrates deeply into porous or microcracked stone, complete extraction may be impossible. Large stone components cannot necessarily be immersed in solvent, and solvent reaching a deeply buried bond can be difficult to deliver safely. Pigments, previous repairs, inscriptions, coatings, and surrounding treatment materials may also be solvent-sensitive.

The distinction is nevertheless meaningful. A cured acrylic bond generally provides future treatment options unavailable with a similarly inaccessible thermosetting epoxy.

This is more appropriately described as increased **retreatability** rather than perfect reversibility.

10.3. Paraloid B-72

Paraloid B-72 is a solid thermoplastic acrylic resin composed principally of ethyl methacrylate and methyl acrylate copolymer. Its usefulness in conservation is supported by decades of practical experience and by a comparatively large body of aging and materials research. Getty conservation terminology identifies it as widely used in conservation and resistant to embrittlement and discoloration under normal conditions, while the current Dow product information emphasizes clarity and flexibility (Dow, n.d.-b; Podany et al., 2001).

B-72 differs operationally from a two-component epoxy because the conservator controls much of its working behavior through solvent selection and solids concentration. A dilute solution can penetrate porous material and act primarily as a consolidant or coating. Increasing the polymer concentration produces a more viscous solution capable of functioning as an adhesive. Very concentrated formulations can become substantially thick and tacky.

This flexibility is both an advantage and a source of variability. Two practitioners describing a repair as “bonded with B-72” may have used substantially different concentrations, solvents, application methods, drying periods, and bond-line thicknesses. Their resulting joints may therefore behave differently even though the nominal polymer is identical.

Any evaluation of B-72 as a structural marble adhesive should consequently specify not only the resin but also the formulation and application procedure.

10.4. The Marble Tests of Podany and Colleagues

The study by Podany, Garland, Freeman, and Rogers remains particularly important because it directly compared B-72 with conventional epoxy and polyester adhesives in marble-to-marble joints.

The researchers adapted standard mechanical tests to evaluate both shear and tensile performance. This distinction was important because large stone assemblies may experience tensile forces perpendicular to a joint as well as conventional shear.

The results challenge the assumption that a soluble acrylic automatically produces a sacrificial adhesive joint. In tensile testing, nearly all B-72 specimens failed within the marble rather than through the adhesive interface. Epoxy and polyester systems likewise produced cohesive marble failure. Across most of the tested systems, the stone itself became the limiting material.

These findings should be interpreted carefully. They do not establish that B-72 is as structurally capable as every epoxy in every configuration, nor do they establish that the same behavior will occur in heavily weathered cemetery marble. The study involved controlled marble specimens and defined laboratory conditions.

What the results demonstrate convincingly is that **solubility and low perceived strength do not guarantee preferential adhesive failure.**

This is one of the most important findings in the literature reviewed for this paper.

10.5. Fracture Toughness and the Jorjani Study

Jorjani and colleagues extended the comparison of thermoplastic and thermosetting adhesives by examining interfacial fracture toughness and bond-line width rather than relying solely on conventional tensile and shear strength.

Eight systems were evaluated: Paraloid B-72, Paraloid B-48N, a 3:1 mixture of B-72 and B-48N, HXTAL NYL-1, Epo-Tek 301-2, Akepox 2000, Marmorkitt 1000, and a layered B-72/Epo-Tek 301-2 system. The researchers specifically tested the hypothesis that thermoplastic resins could provide sufficient structural capacity for marble repair while maintaining greater reversibility than thermosetting adhesives. Several thermoplastic systems were found to be viable from the perspective of interfacial fracture toughness.

The study is important not merely because B-72 performed well. It demonstrates that adhesive selection can be evaluated using properties more closely related to crack initiation and propagation than bulk tensile strength alone.

For historic marble conservation, that approach is particularly relevant. The treatment problem is not simply whether the adhesive can resist a steadily increasing laboratory load. It is whether cracks initiate in the bond, at the interface, or within the stone, and how those cracks propagate once initiated.

A material capable of adequate structural performance while retaining solvent responsiveness is therefore worthy of serious consideration even if its ultimate engineering capacity is lower than that of a high-performance epoxy.

10.6. Paraloid B-48N

Paraloid B-48N represents another acrylic resin of interest in structural stone repair. Dow characterizes the product as a 100 percent acrylic resin offering a combination of toughness, flexibility, adhesion, and exterior durability. Its commercial applications emphasize coatings and adhesion to difficult substrates rather than conservation specifically (Dow, n.d.-a; Jorjani et al., 2008).

Its significance to the present study arises primarily from the Jorjani research, where B-48N was evaluated both independently and as part of a 3:1 B-72/B-48N mixture.

Blending acrylic resins offers an attractive conceptual approach because properties can potentially be adjusted without abandoning thermoplastic behavior. A resin that is somewhat tougher or mechanically different from B-72 could modify joint behavior while preserving greater solvent retreatability than a conventional thermoset.

At present, however, the available marble-conservation literature does not justify assigning a universally preferred B-72/B-48N ratio for exterior monument repair. The laboratory results demonstrate potential, not a field specification.

The blended system should therefore be regarded as an experimental candidate rather than an immediate replacement for established tablet adhesives.

10.7. Glass Transition Temperature and Outdoor Exposure

One of the principal limitations of B-72 for structural exterior use is its relatively low glass-transition temperature. Experimental measurements place the glass transition of dry B-72 near approximately 39–40°C (Vinçotte et al., 2019).

Glass transition does not represent a melting point or an abrupt structural failure temperature. Instead, it marks a temperature region in which an amorphous polymer undergoes a substantial change in molecular mobility and mechanical behavior. As temperature approaches and exceeds this region, the material generally becomes less glassy and more compliant.

This matters in cemetery environments because sun-exposed stone surfaces can become substantially warmer than surrounding air. A structural adhesive whose mechanical properties change appreciably in temperatures attainable by dark or sunlit stone deserves careful consideration where it carries sustained load.

B-72's relatively low glass-transition temperature therefore creates concerns regarding creep and deformation in heavily loaded exterior structural joints. These concerns are less consequential where the adhesive supports a small fragment or where geometry provides independent mechanical support.

This reinforces the structural distinction developed throughout the paper. An adhesive that may be entirely appropriate for reassembling a museum object or a supported fragment may be less attractive as the sole structural connection holding a large exterior monument component under continuous load.

10.8. Residual Solvent and Mechanical Performance

The use of solvent-based thermoplastic adhesives introduces another variable largely absent from two-component epoxies: the adhesive is not fully representative of the dry polymer until sufficient solvent has left the joint.

Research examining residual solvents in B-72 films found that retained solvent substantially depressed the glass-transition temperature. In specimens containing approximately 7.5 percent residual solvent by weight, measured glass-transition temperatures could fall into approximately the 7–10°C range, compared with roughly 39°C for dry B-72 (Vinçotte et al., 2019). This finding has significant implications for structural stone repair.

A thick B-72 bond confined between two relatively impermeable stone surfaces can dry much more slowly than a thin exposed coating. Solvent must migrate out through the joint edges or porous substrate. If substantial solvent remains when the object is placed under load, the adhesive can behave much more softly than anticipated.

The problem is especially relevant to intervention layers, discussed in Chapter 11, because Podany and colleagues emphasized that the B-72 barrier should be **fully dried** before a secondary structural adhesive is introduced.

For exterior monument work, this requirement may create practical difficulties. Cemetery treatment schedules, changing weather, component weight, and the need to complete reassembly can work against prolonged solvent evaporation periods.

A thermoplastic adhesive should therefore not be treated as a simple drop-in replacement for epoxy merely because it remains soluble. Its curing mechanism introduces different installation constraints.

10.9. Solvent Selection

The solvent used to formulate B-72 affects viscosity, evaporation rate, wetting behavior, penetration, working time, and residual-solvent retention. Podany and colleagues tested high-solids B-72 formulations prepared using both acetone and toluene because these solvent systems were already in conservation use.

For field monument conservation, solvent choice also introduces practical health, environmental, and surface-interaction concerns. Rapidly evaporating solvents can produce shorter working periods and may encourage skin formation at exposed surfaces before deeper material has dried. Slower systems extend working time but can increase the period before a thick joint becomes solvent-free.

The effects are sufficiently complex that this paper should not prescribe a single B-72 solvent formulation for structural marble without dedicated testing.

What matters to the broader analysis is that a solvent-based structural adhesive adds **formulation and drying history** to the list of variables governing joint performance.

A two-part commercial epoxy may be comparatively difficult to reverse but offers greater control over polymer composition because the manufacturer determines the formulation. B-72 is more retreatable but places greater formulation responsibility upon the practitioner.

Neither advantage should be ignored.

10.10. Creep and Sustained Loading

Thermoplastic behavior raises a related concern: creep under sustained load.

A material need not fail immediately to produce structural movement. When subjected continuously to stress, polymers can undergo time-dependent deformation. This is especially important when temperature approaches the glass-transition region.

For a vertically oriented tablet fracture, adhesive stresses may vary with wind, handling, and bending rather than remaining continuously large. For a heavy fragment supported entirely through an adhesive joint, sustained shear or tension may be more significant.

This consideration strongly favors separating bearing from bonding where thermoplastic adhesives are being considered. If gravity and mechanical support carry the dead load, an

acrylic adhesive can perform a more limited role associated with alignment or restraint and is correspondingly less exposed to long-duration structural stress.

The same limited-function philosophy proposed for Pratley Putty can therefore apply to thermoplastics for a different reason. With Pratley, limited use reduces the consequences of a strong permanent bond. With B-72, limited structural demand reduces concerns associated with thermoplastic deformation.

Different materials can arrive at similar conservation strategies through different mechanical limitations.

10.11. Exterior Durability

B-72 has a strong conservation record with respect to general aging stability and resistance to discoloration. That record should not, however, be confused with comprehensive evidence for large structural joints exposed continuously outdoors.

Most conservation experience with B-72 involves coatings, labels, small-object repair, consolidation, ceramics, archaeological materials, and objects maintained under comparatively controlled conditions. Exterior stone introduces temperature extremes, direct sunlight, rain, snow, moisture gradients, pollutants, biological growth, and potentially high surface temperatures.

A 2019 study of adhesive systems on granite provides a useful warning. Although not directly transferable to marble, it found that adhesive effectiveness and reversibility were strongly influenced by stone properties and that B-72 intervention layers modified water transport through the treated granite.

Outdoor performance must therefore be evaluated as more than polymer stability. It includes the behavior of the complete adhesive-stone-moisture system.

This distinction is particularly important for grave markers that cannot be protected from rain or direct solar heating.

10.12. B-72 as a Primary Structural Adhesive for Tablet Fractures

The available research demonstrates that B-72 is mechanically more credible for marble repair than its reputation as a relatively gentle conservation resin might suggest.

That does not necessarily make it preferable to AKEPOX 5010 for Gravestone Guardians' routine tablet fractures.

A concentrated B-72 formulation would offer substantially improved chemical retreatability. It would also introduce solvent-drying requirements, potential creep

concerns at elevated exterior temperatures, variable practitioner-controlled formulation, and uncertainty regarding long-term structural behavior through New England seasonal cycling.

AKEPOX 5010 offers permanence and the risk of cohesive marble failure but provides low shrinkage, controlled commercial formulation, useful gel consistency, weather resistance, and a cure mechanism independent of solvent evaporation.

The comparison therefore presents a genuine conservation tradeoff rather than a simple progression from “bad irreversible epoxy” to “good reversible acrylic.”

For a small, well-supported marble fragment, B-72 may offer a compelling balance. For a thin exterior tablet whose repaired fracture must recover substantial bending continuity, the available evidence does not yet establish that B-72 provides a superior long-term field solution.

It should be tested directly.

10.13. Where Thermoplastic Adhesives Appear Most Promising

The evidence reviewed here suggests that thermoplastic acrylics deserve particular consideration for smaller fragments, protected or partially sheltered elements, repairs with independent mechanical support, and applications where future disassembly is highly desirable.

They are also particularly important as **intervention layers**, where they need not provide the entire structural character of the repair by themselves. That role is examined in Chapter 11.

For full structural reassembly of exposed cemetery monuments, the current evidence supports experimentation rather than wholesale substitution.

This is not a minor conclusion. B-72 is one of the most thoroughly accepted synthetic materials in conservation. If even B-72 cannot be selected for structural exterior marble simply from its conservation pedigree, the argument for object-specific treatment selection becomes considerably stronger.

No adhesive escapes the requirement to demonstrate suitability for the particular load, geometry, substrate, and environment.

11. Intervention-Layer Systems

11.1. Separating the Permanent Adhesive from the Historic Stone

Intervention-layer systems attempt to resolve one of the central contradictions in structural conservation: some repairs benefit from the strength and durability of a thermosetting adhesive, yet direct contact between that permanent resin and historic stone reduces future retreatability.

The proposed solution is conceptually straightforward. Before applying epoxy or another permanent adhesive, a thermoplastic resin such as Paraloid B-72 is applied to the historic substrate. After the acrylic layer has dried, the structural adhesive bonds to the acrylic rather than penetrating directly into the marble.

The joint therefore becomes a layered system:

**historic stone → thermoplastic intervention layer → structural adhesive →
thermoplastic intervention layer → historic stone**

In principle, future solvent exposure can soften or dissolve the intervention layer and permit separation of the stone even though the central epoxy remains chemically irreversible.

This approach does not make the epoxy reversible. It changes **where reversibility is introduced into the joint**.

The distinction is subtle but important.

11.2. The Podany Intervention-Layer Study

Podany and colleagues evaluated this concept directly because B-72 barrier coatings were already being used beneath epoxy and polyester adhesives in conservation practice without a sufficiently developed mechanical evidence base.

Their concern was logical. If the structural epoxy no longer penetrates the marble and instead bonds two B-72 coatings together, the performance of the complete joint necessarily depends upon the adhesion and cohesive strength of the acrylic layers. The intervention layer cannot simultaneously isolate the substrate and be ignored mechanically.

The resulting experiments compared marble bonds made with B-72 alone, conventional epoxy and polyester, and combinations in which B-72 served as an interposed barrier beneath those structural adhesives. The results were striking.

In tensile testing, B-72/epoxy barrier assemblies failed at average stresses within the same general range as the marble failures produced by conventional epoxy and polyester systems. Most barrier-layer specimens failed in the marble rather than within the B-72 layer. Similar behavior occurred with B-72/polyester combinations.

The intervention layer therefore did not simply create an intentionally weak release plane.

Instead, the system retained enough structural capacity that the marble frequently remained the limiting material.

11.3. Retreatability Without Sacrificing Strength

The reversibility testing produced the other half of the result. Bonds incorporating B-72 as the primary adhesive or as an intervention layer separated much more readily in an acetone-vapor environment than epoxy used by itself. In the reported tests, B-72-containing joints reversed within the initial test period, while the epoxy-only bond remained intact when testing ended after two months.

Podany and colleagues concluded that a sufficiently thin, conformal, continuous, and fully dried B-72 barrier could substantially increase reversibility without reducing the structural capacity below that required for many large-stone reassembly applications.

This is a significant finding because it separates two properties that are often assumed to be inseparable.

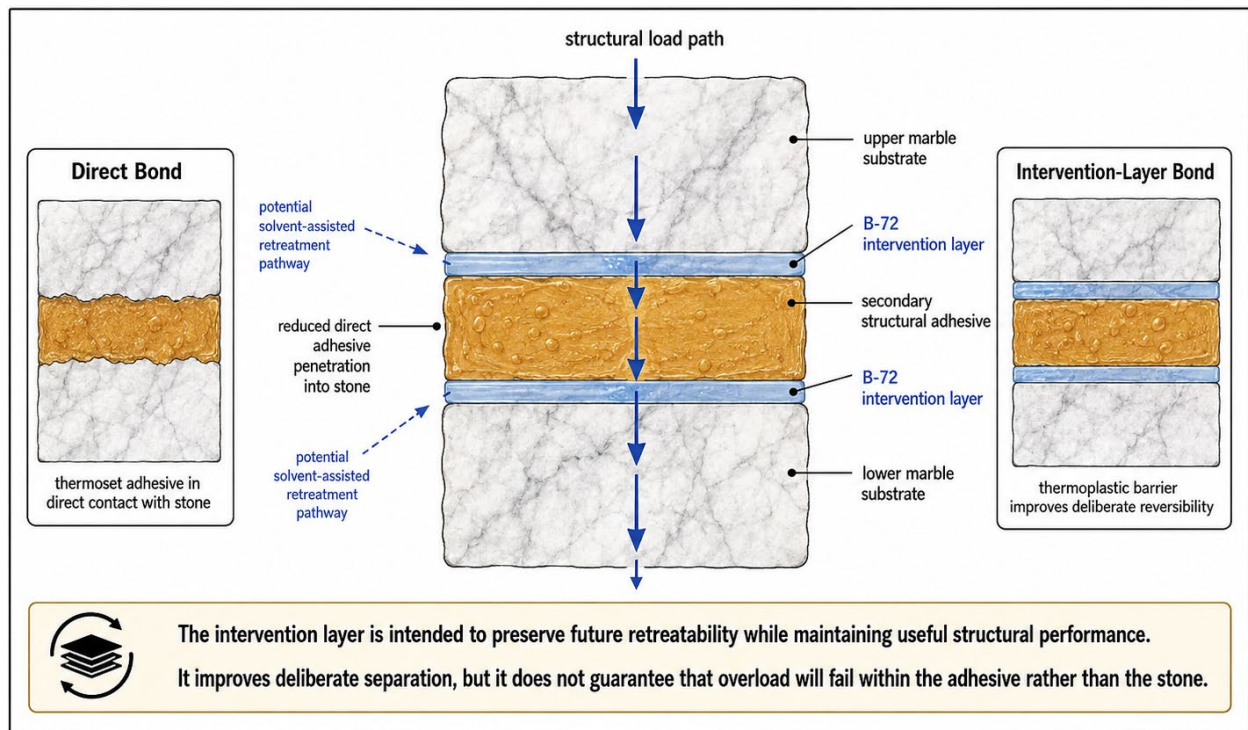
A repair does not necessarily have to become mechanically weak in order to become more retreatable.

For Technical Paper No. 3, that conclusion is highly relevant. It suggests that conservation compatibility can be designed through the **architecture of the adhesive system**, just as Chapters 3 and 6 proposed that sacrificiality can be designed through geometry.

The intervention layer becomes another means of creating system-level behavior rather than relying upon the inherent weakness of one material.

The intervention-layer concept is illustrated schematically in Figure 11.1. A thin thermoplastic barrier separates the historic marble from the permanent structural adhesive, potentially improving deliberate retreatability and limiting direct resin penetration without necessarily changing the location of mechanical failure during overload.

Figure 11.1: B-72 Intervention-Layer System



Note. In this system, Paraloid B-72 is applied as a thin, continuous barrier between the historic stone and a secondary structural adhesive. The barrier is intended to limit direct resin penetration and improve future retreatability, but overall repair behavior still depends on substrate condition, bond geometry, environmental exposure, and loading.

11.4. The Intervention Layer Does Not Guarantee Sacrificial Failure

The same experimental results also create an important warning. If the marble still fails before the intervention layer, then adding B-72 does not necessarily improve the failure hierarchy during an accidental structural overload. It improves retreatability. Those are different outcomes.

This distinction must be kept explicit because otherwise the intervention-layer concept can be oversold. A future conservator may be able to dismantle the joint deliberately with solvent while the assembly remains vulnerable to cohesive marble failure during an uncontrolled impact or overturning event.

The treatment therefore addresses one conservation problem more effectively than another.

This is precisely why the paper distinguishes **failure hierarchy** from **retreatability** rather than treating them as synonyms.

An ideal system would provide adequate service strength, preferentially low-damage failure during overload, and straightforward future disassembly. Existing adhesive technologies may not allow all three objectives to be maximized simultaneously.

11.5. Limiting Resin Penetration

A major theoretical advantage of the intervention layer is its ability to prevent or reduce penetration of irreversible structural resin into the marble.

Low-viscosity epoxies can enter pores and microcracks surrounding a fracture. Once cured, this creates a polymer-influenced zone whose removal may require destruction of adjacent stone. A sufficiently continuous acrylic barrier can occupy or bridge the surface pores first, leaving the subsequent epoxy principally attached to the acrylic film rather than directly impregnating the mineral substrate.

Podany and colleagues identified this limitation of penetration as one of the principal rationales for the intervention-layer method.

For weathered historic marble, this characteristic could be particularly useful. Microcracked or moderately granular surfaces may otherwise permit greater resin uptake than sound laboratory marble.

Yet the same situation raises a paradox. The more deeply the B-72 penetrates into deteriorated marble, the less clearly it behaves as a removable surface film. It can itself become a consolidant within the substrate.

The permanent epoxy may remain isolated from direct stone contact, but the marble has still been altered by acrylic penetration.

This does not eliminate the intervention layer's value, but it reinforces the need to describe reversibility by degree rather than as an absolute condition.

11.6. The Requirement for a Continuous Barrier

For an intervention layer to isolate a permanent adhesive effectively, the film must be sufficiently continuous. Pinholes, missed areas, thin spots, fractures within the coating, or disruption during handling can allow the subsequent epoxy to contact marble directly.

This requirement presents a practical challenge on naturally irregular fracture surfaces. A smooth laboratory coupon can be coated more uniformly than a jagged historic tablet break containing narrow recesses, undercuts, deep pores, friable grains, and sharp edges.

Visual confirmation of full coverage may also be difficult because clear B-72 on white marble can become nearly invisible after drying.

The conservator therefore faces an uncomfortable choice. Applying more B-72 improves the likelihood of continuous coverage but also increases polymer quantity, penetration, and bond-line thickness. Applying less minimizes intervention but may fail to isolate the surface completely.

The success of the system thus depends upon workmanship to an even greater extent than a direct epoxy bond.

Intervention layers should not be described as a simple preliminary coating step. They are an additional engineered interface whose continuity determines how the completed joint behaves.

11.7. The Requirement for Complete Drying

Complete drying is equally important.

Podany and colleagues specifically emphasized that the barrier must be fully dried and solvent-free before the secondary adhesive is placed.

The reasons become clearer when considered alongside later research on residual solvents in B-72. Retained solvent can dramatically reduce the acrylic's glass-transition temperature and alter its mechanical behavior.

If epoxy is applied over a B-72 layer that has not finished losing solvent, the thermosetting resin may effectively cap the surface and further slow evaporation. Solvent could remain trapped within the interface for an extended period, leaving the barrier mechanically softer than anticipated.

The consequences require further investigation. They could include reduced cohesive strength, creep, changes in adhesion between the acrylic and epoxy, void formation, or delayed dimensional change as solvent eventually escapes.

This issue is especially important for exterior cemetery work because practical field schedules can discourage long drying intervals.

If a B-72 intervention layer is ultimately adopted for Gravestone Guardians repairs, drying time and environmental conditions would need to be treated as controlled treatment parameters rather than informal waiting periods.

11.8. Moisture Transport

A significant caution comes from later research on granite cultural heritage.

A 2019 study examined epoxy and acrylic structural adhesives with and without a Paraloid B-72 intervention layer, measuring not only adhesion and reversibility but also capillary

water absorption, water-vapor permeability, color, and microstructure. The researchers found that the B-72 intervention layer improved reversibility but also acted as a barrier to water transport.

The substrate in that research was granite, not marble, and the results cannot simply be transferred quantitatively to historic cemetery stone. The principle, however, is directly relevant.

An acrylic film introduced between two mineral surfaces alters more than adhesive reversibility. It can also alter the movement of liquid water and vapor through that interface.

For a museum sculpture this effect may be relatively unimportant. For an exterior marble monument subjected continuously to rain, condensation, freeze-thaw cycling, ground moisture, and seasonal drying, it deserves much greater attention.

The intervention layer could reduce water penetration through a repaired fracture, which may be beneficial. It could also redirect moisture toward the edges of the film, alter drying gradients, or influence the location at which salts crystallize.

These possibilities should be investigated before intervention layers are described as categorically more compatible with exterior stone simply because the polymer is soluble.

11.9. Intervention Layers and Failure Location

The granite study adds another important observation. Some of the strongest combinations incorporating a B-72 intervention layer still tended to fail within the rock rather than at the adhesive joint. This broadly parallels the earlier marble findings.

The lesson is consistent across both studies: **greater reversibility does not necessarily produce sacrificial mechanical failure.**

This distinction is particularly important for the Gravestone Guardians tablet-repair question. Applying B-72 beneath AKEPOX 5010 could theoretically reduce direct irreversible penetration into the marble and improve future dismantling. It cannot be assumed to make the repaired fracture mechanically safer during future impact.

If the B-72/5010 system still exceeds the cohesive strength of weathered marble, the stone may break elsewhere.

The principal conservation gain may therefore be at the end of the repair's useful life rather than during catastrophic overload.

That can still be a significant gain.

11.10. B-72 Beneath AKEPOX 5010

The existing literature does not appear to provide sufficient published testing specifically evaluating **B-72 as an intervention layer beneath AKEPOX 5010 on naturally weathered exterior marble**. This combination should therefore be considered experimental.

Mechanically, several competing effects can be anticipated. B-72 may reduce penetration of 5010 into the marble and create a solvent-responsive release interface. It also introduces another bond boundary whose quality depends on surface coverage, drying, concentration, and compatibility between the cured acrylic film and the epoxy.

The relatively gel-like consistency of 5010 may make it less penetrative than very low-viscosity epoxies in the first place, potentially reducing one of the intervention layer's advantages. On the other hand, even limited direct epoxy penetration is essentially irreversible, so the ability to isolate the resin from the fracture surface remains attractive.

The appropriate question is therefore not whether the B-72 layer can theoretically be dissolved. It is whether the complete layered joint performs at least as well as direct 5010 bonding under realistic cemetery conditions while producing measurably less stone loss during deliberate retreatment.

That question is well suited to experimental testing.

11.11. B-72 Beneath Pratley Putty

The intervention-layer concept may be even more interesting when considered with localized Pratley Standard Setting Putty.

Because the GG limited-bond model already minimizes adhesive area, adding B-72 beneath each putty pad could potentially create a system with three levels of conservation restraint: stable mineral bearing carries the weight, permanent epoxy putty is confined to selected locations, and a soluble acrylic isolates those locations from direct permanent contact with the marble.

Conceptually, this could substantially improve system-level retreatability. The practical uncertainties are equally substantial.

Pratley is applied as a mouldable, comparatively thick mass rather than a thin resin film. It may impose different peel and shear forces upon the B-72 layer. The acrylic could become the weakest interface and allow premature pad separation, which may or may not be desirable depending upon the required restraint. The pressure used to seat monument components could disrupt or squeeze the intervention layer. Residual solvent could be trapped beneath the putty. Long-term heat and moisture could alter adhesion.

None of these concerns invalidates the idea.

They make it an unusually good candidate for controlled testing.

A direct comparison between Pratley-to-marble and Pratley-to-B-72-to-marble joints could establish whether the intervention layer materially changes ultimate load, displacement, failure location, stone loss, and retreatability.

11.12. Intervention Layers Around Mechanical Reinforcement

The same principle can theoretically be applied to adhesive used around pins or dowels, but the geometry becomes substantially more challenging.

Coating the interior of a drilled hole with B-72 before introducing epoxy could isolate part of the permanent resin from direct stone contact. However, the acrylic would become part of the load-transfer interface between pin, epoxy, and marble. The mechanical performance of the anchorage would therefore depend upon the intervention layer.

This is not a minor issue. A dowel hole is often introduced specifically because substantial structural loads require reliable reinforcement. Introducing an insufficiently characterized thermoplastic layer into a safety-critical anchorage could reduce capacity or increase creep.

The solvent would also have fewer pathways for evaporation from a deep narrow hole, making complete drying difficult to verify.

Intervention layers should therefore be approached more cautiously in drilled structural anchorages than in accessible fracture surfaces or localized horizontal pads.

The objective of reversibility must not compromise the structural reason the pin was installed.

11.13. Barrier Layers and Staining

Another potential benefit of intervention layers is reduction of staining caused by migration of resin components into porous stone.

Conservators have long expressed concern that uncured or partially cured components of thermosetting adhesives can migrate into absorbent marble and produce darkening or discoloration. The use of B-72 beneath epoxy has consequently been recommended in conservation practice partly as a means of isolating the substrate. The Podany research arose in part from precisely this type of field practice and the need to evaluate whether the resulting layered bond retained adequate structural strength.

For white cemetery marble, stain control is especially significant because even small dark halos around a fracture can remain visually prominent.

AKEPOX 5010's gel consistency and low-yellowing formulation already reduce some of the practical risk compared with very fluid conventional epoxies, but they cannot guarantee that resin will never enter microcracks or pores.

An intervention layer may therefore offer aesthetic as well as retreatability benefits.

Again, testing is required to determine whether these benefits outweigh added complexity.

11.14. The Problem of Solvent-Based Retreatability Outdoors

The phrase *solvent reversible* can sound straightforward in a laboratory. A conservator exposes the acrylic to an appropriate solvent, the polymer softens, and the pieces separate.

A cemetery monument creates a much less controlled situation.

The joint may be horizontal, deeply buried, several inches from an accessible edge, and located beneath hundreds of pounds of stone. Delivering solvent uniformly may require extended poulticing, vapor exposure, injection, or partial mechanical opening. Wind and evaporation complicate containment. Nearby biological growth, setting compounds, fills, inscriptions, previous coatings, and adhesives may react differently to the solvent.

Personnel exposure and environmental release must also be managed.

The practical advantage of B-72 should therefore not be expressed as “the repair can simply be dissolved later.” In many large-monument applications that would be unrealistic.

A more accurate statement is that B-72 introduces a **chemically weakenable interface** that may substantially improve future separation compared with direct thermosetting adhesion.

That is still valuable, but it is a more defensible claim.

11.15. Intervention Layers as One Form of System-Level Sacrificiality

Chapter 3 introduced system-level sacrificiality as the idea that conservation compatibility can emerge from the arrangement of multiple materials rather than from requiring every individual component to be weak.

Intervention layers fit directly within that framework.

The epoxy supplies structural capacity. The acrylic limits direct epoxy penetration and creates a potentially weakenable interface. Bearing materials may carry dead load

independently. Perimeter compounds remain replaceable. Documentation identifies the location and formulation of the permanent adhesive.

No single layer accomplishes every conservation objective.

The repair becomes conservative through **division of function**.

This architecture is conceptually similar to the Gravestone Guardians use of lead, Pratley Putty, and setting compound. In both systems, the desired outcome is achieved not by finding one ideal material but by assigning different functions to materials selected for those roles.

That convergence suggests a potentially productive path forward: intervention layers may be most useful not as a universal coating beneath every adhesive but where they reinforce an already restrained treatment philosophy.

11.16. A Proposed Experimental Matrix

The intervention-layer question should be tested directly rather than resolved through literature analogy.

For closely fitting tablet joints, meaningful comparisons would include direct AKEPOX 5010, B-72 alone, B-72 followed by AKEPOX 5010, and potentially a B-72/B-48N system or blend identified through the conservation literature.

For multi-piece restraint, comparisons should include direct Pratley Putty pads and Pratley pads applied over a controlled B-72 intervention layer.

Specimens should be evaluated before and after environmental aging. Mechanical testing should record ultimate load, displacement, stiffness, location of failure, percentage of cohesive stone failure, depth or volume of stone loss, and the ability to separate the remaining joint deliberately.

Hydric behavior should also be considered. The 2019 granite research demonstrates that intervention layers can change capillary and vapor transport, so moisture response should not be omitted merely because the principal research question concerns adhesive strength.

A successful intervention-layer system would therefore need to demonstrate more than solvent sensitivity.

It should provide adequate service capacity, acceptable environmental behavior, and materially improved retreatability without shifting the overload failure mode farther into the marble.

11.17. Conservation Implications of Intervention Layers

Intervention layers represent one of the most promising concepts examined in this paper, but also one of the easiest to oversimplify.

The evidence establishes that a B-72 layer can significantly increase the retreatability of structural marble joints while retaining substantial mechanical capacity. The concept is therefore far more than theoretical conservation doctrine.

At the same time, the evidence does not demonstrate that the barrier makes the joint mechanically sacrificial. Marble failure can still occur. Exterior water transport can be altered. Residual solvent can change acrylic behavior dramatically. Field application to irregular weathered fracture surfaces is more difficult than laboratory preparation.

For Gravestone Guardians, B-72 intervention layers should consequently be regarded as **high-priority research candidates rather than immediate standard procedure.**

If testing establishes that they meaningfully improve retreatability beneath AKEPOX 5010 or localized Pratley Putty without creating unacceptable outdoor durability or moisture problems, they could strengthen the limited-bond philosophy considerably.

If they do not, direct limited application of a carefully selected permanent adhesive may remain the more predictable treatment.

Either outcome would be valuable evidence.

12. Mineral Grouts, Mortars, and Inorganic Adhesive Systems

12.1. Why Mineral Materials Deserve Separate Consideration

The conservation preference for mineral repair materials is understandable. Marble itself is mineral. Historic monuments were traditionally assembled with stone, lime-based mortars, metals, and other inorganic materials long before synthetic polymer adhesives became available. Mineral grouts and mortars can offer moisture permeability, thermal behavior, visual compatibility, and long-term aging characteristics more closely related to masonry than those of an organic polymer.

These advantages have sometimes led to the broader assumption that mineral materials are inherently more conservation-compatible than epoxy.

That assumption requires the same scrutiny applied to polymer adhesives.

A mineral material can be excessively strong, stiff, dense, salt-bearing, shrink-prone, chemically incompatible, difficult to remove, or inappropriate for the loading condition in which it is used. Conversely, a polymer may be mechanically appropriate in a narrowly defined structural role even though its chemistry differs markedly from the stone.

The relevant question is therefore not whether a material is mineral or synthetic.

It is what the material is being asked to do.

This distinction becomes especially important when injection grout is proposed as an alternative to epoxy for joining a broken marble tablet. Grout can provide excellent performance within voids and distributed masonry systems while remaining poorly suited to a narrow fracture expected to carry significant tension or bending.

Mineral compatibility and structural function must be evaluated separately.

12.2. The Difference Between Adhesion and Grouting

An adhesive is commonly expected to create a bond between surfaces and transfer meaningful tensile or shear stresses across that bond.

Injection grout traditionally serves a different function. It is introduced into cracks, cavities, separations, or void networks in order to fill space, restore contact, redistribute compression, reconnect detached layers, or improve the internal coherence of a masonry assembly.

These functions can overlap. A grout can possess substantial bond strength, and an adhesive can fill a void. The categories nevertheless remain useful because their material design and expected loading differ.

The Getty Conservation Institute's extensive research into lime-based injection grouts focused principally on conservation of delaminated architectural surfaces, including wall paintings, plasters, and mosaics. The program evaluated properties such as injectability, splitting tensile strength, capillary water absorption, shrinkage, and compatibility because successful grouting depends on much more than compressive strength.

The RILEM work associated with that program likewise concerned specifications for **non-structural grouting** of historic masonry and architectural surfaces.

This context matters. A material developed to reconnect a delaminated plaster or fill internal masonry voids should not automatically be treated as a substitute for a structural fracture adhesive in a free-standing marble tablet.

12.3. Mineral Compatibility Does Not Mean Mechanical Weakness

One of the more important corrections required in discussions of injection grout is the assumption that a cementitious or lime-based material must necessarily be much weaker or more flexible than epoxy. That is not universally true.

Different mineral grout formulations can develop very substantial compressive, flexural, and bond strengths. Hydraulic binders can also produce relatively high stiffness once cured. Their advantages may lie in porosity, thermal compatibility, capillary behavior, chemistry, and distributed load transfer rather than in being mechanically weak.

This becomes particularly clear when examining Heritage IG10 Injection Grout.

IG10 is described by U.S. Heritage Group as a single-component, cement-based injection grout containing mineral binders and no synthetic polymers or additives. It is intended to stabilize and repair historic masonry and concrete and is formulated for injection into cracks approximately 1/16 to 1/4 inch wide (U.S. Heritage Group, n.d.; see Appendix J).

Its mineral composition should not be confused with a soft lime putty.

The manufacturer's published data report substantial mechanical properties, including 28-day compressive strength around 7,300 psi, bond strength around 1,815 psi, flexural strength around 1,700 psi, and an elastic modulus around 2,350 ksi under the referenced ASTM tests. Porosity is listed near 6 percent and absorption at approximately 4–6 percent (U.S. Heritage Group, n.d.; see Appendix J).

Those figures do not make IG10 inappropriate. They demonstrate that the material should be regarded as a high-performance cementitious grout rather than as an inherently weak sacrificial filler.

12.4. IG10 as a Case Study

IG10 is especially relevant because it is sometimes considered for historic marble repair precisely as an alternative to epoxy.

The manufacturer's intended use supports many conservation applications. It is designed for cracks and voids in historic masonry, contains no synthetic polymer, is described as low shrink, and develops substantial bond strength (U.S. Heritage Group, n.d.).

Those characteristics could make it attractive for internal voids, cracks of sufficient width, separations within masonry assemblies, or situations in which mineral continuity is preferable to polymer filling.

They do not automatically establish it as an optimal adhesive for rejoining two halves of a broken tablet.

A tablet fracture subjected to bending needs to transmit tension across the break. The joint may be irregular, close-fitting, and much narrower through portions of its depth than the crack widths for which the grout is designed. Successful application would require complete grout penetration without voiding, reliable adhesion to both fracture surfaces, appropriate curing moisture, and sufficient tensile continuity after hardening.

Even if those conditions are achieved, the cured grout is relatively stiff and strong. If the purpose of replacing epoxy with IG10 is to create a deliberately weak sacrificial joint, the published mechanical data do not support assuming that outcome.

The grout could still exceed the local tensile or cohesive capacity of severely weathered marble.

The question must therefore be tested rather than inferred from the word *mineral*.

12.5. Comparing IG10 With Structural Epoxy

Direct numerical comparison between IG10 and AKEPOX 5010 should be approached cautiously because the reported properties come from different test standards and describe different material behaviors.

AKEPOX 5010 reports high tensile and flexural properties for a polymer structural adhesive. IG10 reports compressive, bond, flexural, and modulus properties for a cementitious injection grout. The test geometries and failure mechanisms are not equivalent.

Qualitatively, however, several distinctions are clear.

AKEPOX 5010 can form a very thin bond line and develops its properties through chemical curing largely independent of evaporation or hydraulic moisture exchange. It is essentially impermeable relative to mineral grout, permanently cross-linked, and capable of strong adhesion across narrow stone fractures.

IG10 requires water for mixing and hydraulic cure, occupies greater physical volume, contains mineral binder, possesses measurable porosity and absorption, and is designed to fill cracks and voids rather than form an exceptionally thin polymer film (U.S. Heritage Group, n.d.).

The two materials therefore create fundamentally different repaired joints.

Calling one “strong” and the other “compatible” obscures the actual decision.

12.6. Stiffness and the IG10 Question

IG10's published elastic modulus is particularly relevant to the conservation argument. The reported value of approximately 2,350 ksi converts to roughly 16 GPa (U.S. Heritage Group, n.d.).

That value should not be compared directly with epoxy modulus figures from unrelated test methods as though it establishes a simple ranking. It does demonstrate that cured IG10 is not an extremely compliant material. This is important for weathered marble.

If a relatively stiff cementitious grout fills a fracture within marble whose grain cohesion has been substantially reduced, the same mechanical question arises as with epoxy: where does strain accumulate when the assembly moves?

The mineral grout may possess advantages in thermal expansion and moisture behavior, but it can still create a mechanically distinct region. This is why conservation compatibility must remain multidimensional.

A material can be chemically and hydrologically more compatible with stone while still being mechanically too stiff for a particular deteriorated substrate.

12.7. Porosity and Moisture Transport

Mineral grouts possess a major potential advantage over dense polymer adhesives: many retain interconnected pore structures that permit movement of liquid water and vapor.

IG10's manufacturer reports measurable porosity and water absorption, illustrating this difference from a dense epoxy film (U.S. Heritage Group, n.d.).

Lime-based hydraulic grouts are similarly valued in conservation partly because their pore structure and mineral chemistry can be tailored to surrounding historic masonry. Getty's grout research includes capillary water absorption among the properties considered essential to compatibility.

This does not mean that the grout should simply match the stone numerically. A repair material whose absorption is substantially higher or lower than adjacent marble can alter wetting and drying patterns. The size and connectivity of pores also matter, as do salts and curing products.

Nevertheless, the ability of mineral systems to participate in moisture transport can be advantageous in exterior monuments where a continuous polymer barrier might redirect moisture.

This advantage becomes more meaningful as the treated area increases.

For a very thin fracture line, the overall hydrologic effect of epoxy may be modest. For a large bedding interface, broad injection zone, or extensive void fill, permeability differences become more consequential.

12.8. Thermal Behavior

Mineral materials can also offer thermal-expansion behavior closer to stone than many polymers.

IG10's published linear coefficient of thermal expansion falls within a mineral-material range and is reported by the manufacturer as approximately $3.9\text{--}5.5 \times 10^{-6}$ per degree Fahrenheit under the listed conditions (U.S. Heritage Group, n.d.).

This is potentially advantageous in an exterior monument undergoing repeated thermal cycling. A grout whose expansion and contraction broadly resembles masonry may generate less differential movement than an organic polymer with a substantially different coefficient.

Again, similarity in one property does not establish overall compatibility.

Marble itself is anisotropic, weathered historic stone contains microcracks, and the joint geometry can dominate local stress distribution. The value nevertheless reinforces why mineral systems deserve a legitimate place within the treatment toolbox rather than being treated simply as weak substitutes for “real glue.”

Their strengths often arise from **material affinity and distributed behavior**, not from maximum adhesion.

12.9. Shrinkage

Shrinkage is a critical property of injection grouts because loss of volume during cure can reduce contact with surrounding stone and undermine the purpose of filling the void.

US Heritage describes IG10 as low-shrink or non-shrink within its product literature (U.S. Heritage Group, n.d.).

Lime-based hydraulic grouts more broadly can experience significant shrinkage depending upon water content, binder composition, aggregate, curing conditions, and substrate absorption. Recent research on natural hydraulic lime grouts continues to identify shrinkage control as a major conservation issue.

This is particularly relevant when considering grout for fracture joining.

A small amount of separation developing between grout and stone may be relatively tolerable in a large irregular masonry void where many contact points remain. In a narrow structural fracture that depends upon complete continuity across the joint, the same shrinkage can materially reduce performance.

The tolerance for shrinkage therefore depends upon the structural role.

12.10. Lime-Based Hydraulic Injection Grouts

Lime-based hydraulic grouts occupy a somewhat different conservation position from specialty cementitious products such as IG10.

The Getty Conservation Institute devoted a major research program to developing reliable methods for evaluating lime-based hydraulic injection grouts used in conservation. The work recognized that conventional standardized tests developed for Portland-cement mortars were not necessarily appropriate for conservation injection grouts and emphasized a wider range of performance properties.

Natural hydraulic lime and lime-pozzolan systems can be formulated to develop sufficient hydraulic setting in confined damp environments while retaining greater compatibility with traditional masonry than conventional high-Portland-cement grouts.

Research on NHL grouts continues to focus on composition, injectability, shrinkage, strength, substrate interaction, and curing. Recent work describes NHL grouts as attractive for historic masonry because of their compatibility in strength and porosity, while simultaneously acknowledging that shrinkage can undermine their performance.

These materials are particularly compelling where the repair objective is to fill voids or reconnect mineral layers rather than to reproduce the tensile performance of a structural polymer.

12.11. Grout Injectability

A grout cannot stabilize a void it cannot reach.

Injectability depends upon particle size, viscosity, yield stress, water content, void geometry, substrate absorption, injection pressure, and the tendency of solids to separate from the liquid phase.

Getty's research treated injectability as a fundamental property and developed laboratory procedures specifically to compare the ability of conservation grouts to pass through porous media representing architectural voids.

This is particularly relevant to marble fracture repair because the visible width of a crack does not describe its internal geometry. A break may be open near the surface but close tightly deeper within the stone. Mineral particles that flow readily into the visible opening may bridge or filter at narrower locations, leaving hidden voids.

A low-viscosity epoxy can often wet and penetrate these irregular interfaces differently because it contains no suspended mineral aggregate of comparable scale.

The ability to inject IG10 into cracks down to the manufacturer's stated range is useful, but that capability does not demonstrate complete filling of a closely fitting tablet fracture of variable width (U.S. Heritage Group, n.d.).

The geometry should determine the material, not merely the existence of a crack.

12.12. Injection Pressure

Pressure is another important distinction between adhesive placement and grout injection.

A fracture adhesive is typically applied to accessible broken surfaces before the components are brought together. Injection grout is frequently introduced after surfaces or layers are already in position.

Pressure sufficient to move grout through a narrow void can also exert force on the weakened material surrounding that void. In delaminated plaster, fragile stone veneers, or severely cracked marble, excessive pressure can enlarge separations or create new fractures.

Conservation grouting therefore emphasizes controlled injectability rather than simply increasing pressure until material flows.

For a broken tablet that can be safely separated and dry-fitted, applying a suitable adhesive directly to the accessible fracture surfaces may provide more reliable coverage than attempting to inject mineral grout into the closed break afterward.

Injection becomes more attractive where disassembly is undesirable or impossible.

12.13. Grout as a Delamination Treatment

One of the clearest legitimate applications for mineral injection grout in historic marble is internal delamination or voiding where intact stone surfaces remain in place but have separated locally.

Examples might include a thick monument component containing internal separation, a veneer or applied marble element detaching from a mineral backing, voids behind architectural fragments, or historic fills that have lost contact.

Here the grout does not need to recreate a narrow tensile fracture as though the stone had never broken. It can fill void space, increase contact area, and redistribute loading over a broader mineral interface.

These conditions correspond much more closely with the applications studied in conservation grout research. Getty's program specifically addressed the use of injection grout to fill voids and reattach delaminated architectural surfaces.

In such circumstances, a compatible mineral grout may offer substantial advantages over filling the cavity with epoxy.

12.14. Grout as a Tablet-Fracture Adhesive

The use of injection grout to join a fully separated tablet deserves greater caution.

A fractured vertical tablet requires the repaired section to transmit bending stresses, including tension. Mineral grouts generally perform much better in compression than in direct tension. Their brittle mineral structure and required bond thickness can make them less suited to the very thin high-tension interface created by a clean fracture.

IG10's published bond and flexural strengths demonstrate that the material is by no means mechanically insignificant. The question is whether those properties translate into a more favorable **failure hierarchy** than an epoxy fracture adhesive (U.S. Heritage Group, n.d.).

If IG10 bonds strongly enough that weathered marble breaks adjacent to the grout, its mineral composition provides little sacrificial advantage during overload. If the grout fails prematurely under routine bending or develops microcracks through freeze-thaw and thermal cycling, the treatment may require repeated intervention.

A comparison with AKEPOX 5010 should therefore examine not only which specimen carries more load but where each system fails, how much original marble is lost, and how performance changes after aging.

Until such evidence exists, IG10 should not be described as either clearly superior or clearly unsuitable for every marble fracture.

Its published intended use and material geometry, however, suggest that it is **better aligned with void filling and crack injection than with routine reassembly of cleanly separated tablets.**

12.15. Mortars as Bedding Materials

Mortars occupy yet another role.

A bedding mortar can distribute compression across irregular surfaces, establish full support, fill larger mineral voids, and provide an interface that is potentially more compatible and replaceable than structural epoxy.

This role can be highly appropriate beneath broad monument components where the objective is stable bearing rather than tensile bonding.

The distinction between bedding mortar and adhesive is essential. A bedding material should not necessarily prevent the upper monument component from ever separating. Its purpose may instead be to create uniform contact and transmit compression while accommodating small irregularities.

In the limited-bond model, a mineral bedding material could theoretically complement localized adhesive restraint in much the same way as lead wedges, provided the mortar is appropriate for the stone, joint thickness, moisture conditions, and load.

The treatment should avoid rigidly encapsulating a monument interface with unnecessarily strong mortar merely because mineral material is considered traditional.

12.16. Lime Mortar and Sacrificiality

Traditional lime mortars illustrate genuine material-level sacrificiality more clearly than most structural adhesives. They can be formulated with lower strength and greater deformability than the masonry units they join, allowing deterioration to occur preferentially within the replaceable joint. That principle has considerable value at exposed monument joints.

It is less directly transferable to a clean structural fracture. A mortar soft enough to remain comfortably sacrificial may simply lack the tensile continuity required to restore a thin broken tablet.

This distinction should prevent inappropriate extrapolation from architectural repointing doctrine.

A good pointing mortar and a good fracture adhesive solve different problems.

Conservation becomes more effective when these different functions are allowed to remain different.

12.17. Hydraulic Versus Nonhydraulic Lime

Lime-based repair materials vary substantially according to binder chemistry.

Nonhydraulic lime relies primarily upon carbonation and requires access to atmospheric carbon dioxide for conversion of calcium hydroxide toward calcium carbonate. Deep confined joints can carbonate very slowly.

Hydraulic lime develops strength partly through hydration reactions and can therefore set more effectively in thicker, damp, or poorly ventilated locations. Natural hydraulic lime and lime-pozzolan systems are consequently more practical for many injection-grout applications.

The increased hydraulicity that improves setting can also increase strength and stiffness. Selection therefore requires balance.

The binder should be sufficiently hydraulic to cure reliably within the intended location without developing unnecessarily high properties relative to the historic substrate.

This is another example of the paper's larger principle: more strength is useful only until adequate performance has been achieved.

12.18. Cementitious Grouts and the Portland Cement Question

The conservation community has long expressed caution regarding Portland cement in historic masonry because high strength, stiffness, density, soluble salts, and differences in moisture behavior can create incompatibility with softer historic materials.

That concern should not be converted into a prohibition based merely upon the presence of cement chemistry.

Modern specialty conservation grouts can be engineered very differently from conventional structural concrete or high-strength masonry mortar. IG10, for example, is specifically

marketed for historic masonry despite being cement based and uses a controlled mineral formulation without synthetic polymer additives (U.S. Heritage Group, n.d.).

The appropriate evaluation should examine measured properties and intended function rather than product-category labels.

At the same time, the presence of a heritage-oriented formulation does not remove the need to compare its stiffness and strength against fragile marble.

A product designed to stabilize robust historic masonry may still be too mechanically aggressive for a severely sugared two-inch tablet.

The substrate remains decisive.

12.19. Mineral Grouts and Retreatability

Mineral grouts are often described as more reversible than epoxy because they can sometimes be mechanically removed more readily and do not penetrate stone as a cross-linked polymer film. That advantage varies enormously with application.

A soft lime fill exposed at a joint can be readily raked out and replaced. A high-strength cementitious grout injected deeply into a network of internal cracks may be effectively permanent. Mechanical removal could require widening the fracture or removing surrounding original stone.

Again, chemistry does not determine practical reversibility by itself.

Injection itself can make a material less retreatable because the treatment becomes distributed through inaccessible internal space.

A mineral material can therefore be chemically compatible and practically irreversible.

Documentation is especially important in such treatments because future practitioners may have no visual indication of the volume or extent of grout concealed within the stone.

12.20. Mineral Repair Mortars and Lithomex-Type Materials

Mineral repair mortars such as Lithomex occupy a useful position between pointing mortars and structural grouts. They are principally designed to replace missing mineral volume, reconstruct edges or profiles, and provide visually and physically compatible repairs to masonry rather than act as high-performance structural adhesives.

For monument conservation, this can be highly beneficial.

A broken tablet repaired with a thin structural adhesive may still contain small losses along the fracture. Those losses need not necessarily be filled with the same epoxy used to join

the pieces. A mineral repair mortar can perform the cosmetic and protective loss-compensation role while the adhesive remains confined to the actual fracture surfaces.

This separation reduces polymer volume and produces a visible repair material more similar in texture and weathering behavior to the stone.

The same principle applies to damaged monument joints and chipped edges.

Structural adhesive should not become the default fill merely because it is already being mixed.

12.21. Combining Mineral and Polymer Systems

The most productive direction may not be choosing between mineral and polymer materials at all.

A single monument repair can assign different roles to each.

A closely fitting tablet break might use a minimum quantity of structural epoxy for fracture continuity and mineral repair mortar only where material is missing.

A multi-piece monument might carry dead load through stone, lead, and possibly appropriate mineral bedding while localized polymer restraint protects against displacement.

A delaminated internal void might receive lime-based or compatible cementitious injection grout without any need for structural epoxy.

A surface loss might receive mineral restoration mortar while an independent concealed pin addresses a truly necessary structural load.

These combined systems are more complex than selecting one universal “compatible” material, but they more accurately reflect the different forces and deterioration processes occurring within historic monuments.

Conservation compatibility emerges through **assignment of function**.

12.22. Where IG10 Fits in the Gravestone Guardians Toolbox

IG10 appears to have a legitimate and potentially valuable role within a Gravestone Guardians material system, but that role should be more precisely defined than “mineral alternative to epoxy.”

Its strongest candidates include injection into appropriate voids and separations, filling cracks within the manufacturer’s practical injection range where distributed mineral

bonding is desired, and stabilization of masonry conditions for which a high-performance cementitious grout is appropriate.

It may also deserve experimental evaluation in wider marble fractures or fragmented assemblies where the joint geometry provides sufficient grout volume and the loading is predominantly compressive or shear rather than high bending tension.

Its weaker candidate is the clean, close-fitting transverse fracture through a thin marble tablet that must regain substantial bending continuity.

AKEPOX 5010 is materially better suited to occupying an extremely thin fracture and transmitting tension. Whether IG10 could provide an acceptable lower-damage failure hierarchy in that condition remains a research question, but its mineral composition alone does not establish that advantage.

This distinction is important enough to state plainly:

Injection grout should not be treated as epoxy with better conservation credentials. It is a different material intended to solve a different class of structural problems.

12.23. Preliminary Material-Role Framework

The mineral systems examined in this chapter can be summarized according to function rather than product preference.

Table 12.1: Preliminary Material-Role Framework for Mineral Systems

Material family	Most defensible conservation role	Principal advantage	Principal limitation
Specialty cementitious injection grout such as IG10	Internal voids, cracks of suitable width, masonry consolidation, distributed mineral repair	Strong mineral bond, measurable porosity, no polymer binder, low-shrink formulation	Relatively high strength and stiffness; not automatically sacrificial; difficult retreatment when deeply injected
NHL/lime-pozzolan injection grout	Delamination, void filling, compatible masonry consolidation	Adjustable strength and porosity; mineral compatibility; hydraulic setting	Shrinkage, slower strength development, formulation sensitivity, limited tensile structural capacity

Material family	Most defensible conservation role	Principal advantage	Principal limitation
Lime bedding mortar	Broad compression-bearing interfaces	Replaceability, distributed bearing, accommodation of irregularity	Limited tensile restraint; inappropriate as substitute for required anchorage
Mineral repair mortar	Edge loss, fracture losses, cosmetic and protective compensation	Texture and mineral compatibility; reduces need for polymer fills	Not generally a primary structural fracture adhesive
Lime pointing/joint material	Exposed sacrificial perimeter joints	Maintenance-friendly and comparatively replaceable	Should not be relied upon for major structural restraint

The table does not establish universal prescriptions. It illustrates how mineral materials become most useful when selected for the functions they perform particularly well.

12.24. The Significance of Mineral Systems to Failure Hierarchy

Mineral materials contribute to failure hierarchy in ways that extend beyond adhesive strength.

A replaceable lime perimeter joint can fail and be renewed without dismantling the monument. A mineral bedding layer can distribute compression and reduce point loading. Injection grout can reconnect separated internal material without coating an entire exterior interface with polymer. Repair mortar can replace missing edge volume without enlarging the structural adhesive bond. These are significant conservation advantages.

Yet mineral systems can also produce unfavorable hierarchy if selected poorly. A very strong grout injected into friable marble may become the most durable component while surrounding stone deteriorates. Rigid cementitious bedding can concentrate stress. Dense repairs can redirect moisture. Shrinkage can create hidden voids. Inaccessible grout can become effectively impossible to remove.

The word *mineral* therefore carries no automatic guarantee of sacrificial behavior.

The same analytical discipline applied to epoxies must apply here.

12.25. A Research Opportunity: IG10 Versus AKEPOX 5010

Given the interest in injection grout as an adhesive for broken marble, direct comparative testing would be particularly valuable.

A useful experiment should not attempt merely to demonstrate whether IG10 can hold two pieces of marble together. It almost certainly can under some conditions.

The more relevant comparison would evaluate sound and weathered marble specimens repaired with AKEPOX 5010 and IG10 under matched fracture geometries where each material can be applied appropriately.

Testing should record initial joint strength, stiffness, displacement before failure, fracture location, depth and amount of cohesive marble loss, performance after wet-dry and freeze-thaw cycling, visible cracking within the grout, and practical retreatability.

The geometry must be selected carefully because forcing IG10 into a bond line substantially narrower than its intended use would unfairly test the material outside its design function. Conversely, widening a historic-style fracture merely to accommodate grout would itself represent an unrealistic conservation intervention.

A second series using naturally wider or chipped fracture geometries could therefore be particularly informative.

Such testing could finally replace anecdotal arguments about whether grout is “better for the stone” with measurable evidence concerning what actually happens when the repaired assembly fails.

12.26. Mineral Systems and the Limited-Bond Model

The strongest implication of this chapter is that the Gravestone Guardians limited-bond philosophy need not be understood as a polymer-based treatment system.

Its essential principle is functional separation.

Stable stone and suitable bearing materials carry compression. Mineral bedding or repair material can address irregular contact where appropriate. Localized adhesive supplies restraint only where restraint is needed. Perimeter materials remain maintainable. Injection grout addresses internal voids rather than being expected to substitute for every adhesive joint.

This approach potentially combines the most useful characteristics of mineral and polymer materials without requiring either to perform outside its ideal role.

Such a system is inherently more complicated than a single-product repair specification. It requires diagnosis, dry fitting, material selection, and documentation. That complexity is not a weakness.

Historic monuments are already complex material systems. A conservation treatment that recognizes that complexity is more likely to preserve the stone than one that attempts to solve every problem with either epoxy or mortar.

12.27. Conservation Implications for Mineral Systems

Mineral grouts and mortars should occupy a substantial place within historic marble conservation, but their value should be stated accurately.

They are particularly advantageous for distributed void filling, bedding, delamination repair, compatible loss compensation, and maintainable perimeter joints. Their mineral composition, porosity, and thermal behavior can offer important advantages over dense structural polymers.

They should not be presumed to provide a safer structural fracture joint merely because they are inorganic.

IG10 illustrates this point particularly well. It is a sophisticated, high-performance cementitious conservation grout with no synthetic polymer additives and significant published mechanical capacity. Those characteristics make it highly useful for appropriate masonry applications. They also mean it cannot be described credibly as a soft sacrificial alternative to epoxy without comparative testing (U.S. Heritage Group, n.d.; see Appendix J).

Lime-based hydraulic grouts may offer lower-strength and more porous options, but they too must be evaluated for shrinkage, injectability, curing, substrate compatibility, and actual load requirements. Getty's research program exists precisely because conservation grout selection cannot be reduced to binder name alone.

For Gravestone Guardians, the resulting position should be deliberately pluralistic.

AKEPOX 5010 remains a plausible material for narrow structural tablet fractures. Pratley Putty remains a candidate for localized restraint within independently supported multi-piece assemblies. Mineral grouts such as IG10 belong primarily in voids, suitable cracks, and distributed masonry repairs. Lime-based mortars and mineral restoration materials should perform bedding, pointing, and loss-compensation functions where their properties are better matched to those roles.

The objective is not to determine which of these materials is universally “best for marble.”

It is to prevent any one of them from being asked to perform work for which another material—and another repair geometry—would preserve more historic stone.

13. Lead Wedges, Shims, and Bearing Materials

13.1. Bearing Is a Structural Function

The discussion of adhesives can easily obscure a simpler mechanical reality: before a monument component can be bonded, pinned, pointed, or sealed, it must be supported.

In a properly assembled multi-piece monument, the downward force created by the upper component should pass through stable bearing into the component beneath it. Adhesive may supplement that assembly by resisting sliding or separation, but it should not ordinarily be required to compensate for fundamentally inadequate contact between the stones.

Bearing therefore deserves the same level of consideration as adhesive selection.

If two nominally flat monument surfaces actually contact at only several irregular high points, the upper component's weight is concentrated through those areas. A stone that would readily support the total load over a broad surface can experience substantially greater localized stress when the contact area is reduced. Small edge chips, residual mortar, old adhesive, weathered grains, or natural surface irregularities can therefore create point loading even when the monument appears to be seated correctly.

Shims and wedges provide a means of controlling this contact. Their role is not primarily to bond the monument together. They establish elevation, level, joint spacing, and selected bearing points while compensating for small irregularities between surfaces.

This distinction is central to the Gravestone Guardians limited-bond model because it allows the adhesive and the bearing system to perform different jobs.

13.2. Lead as a Traditional Bearing Material

Lead has a long history in architectural and monument work because its physical characteristics are unusually useful where a relatively soft metal must conform between much harder materials. Historic England describes lead as notably soft and readily worked, characteristics that historically contributed to its broad architectural use (Historic England, 2022).

Within monument setting, thin lead wedges or strips can deform slightly under load and accommodate small imperfections in adjacent stone surfaces. This differs from placing a similarly sized piece of hard steel between marble components. A hard shim contacting a small surface defect can transmit a highly concentrated load, whereas softer lead can deform and increase the effective contact area.

This characteristic helps explain the persistence of lead within monument-setting practice even though numerous modern plastic and metal shim materials are available.

Lead also permits fine incremental adjustment. A wedge can be inserted or moved gradually until a die or monument section reaches the desired level and plumb. Once the upper component is seated, the lead remains as part of the bearing interface.

Contemporary conservation specifications demonstrate that this practice continues. A Town of Nantucket cemetery conservation specification identifies resetting detached markers using a combination of bonding agent, lead wedges, and monument setting compound. Commercial monument-setting practice likewise continues to describe lead placement beneath monument corners during final setting (Atlas Preservation, n.d.-a; Town of Nantucket, 2022).

Such documentation does not establish lead as universally required. It confirms that lead wedges form part of an established monument-setting tradition with recognizable mechanical purposes.

13.3. Conformability and Load Distribution

The primary mechanical advantage of lead is conformability.

No historic stone interface is perfectly planar at the microscopic level. Even polished monument surfaces contain slight irregularities, while hand-finished or weathered marble can vary considerably. When a relatively soft shim is placed between these surfaces and loaded, the shim can deform around small asperities rather than forcing the entire load through the highest point.

This deformation can improve contact and reduce localized stone stress.

The effect should not be exaggerated. A narrow wedge remains a narrow support. It cannot transform a severely uneven interface into broad uniform bearing by itself. If the monument rests primarily on four tiny lead pads while almost no stone-to-stone or distributed bedding contact exists elsewhere, substantial loads remain concentrated through relatively small areas.

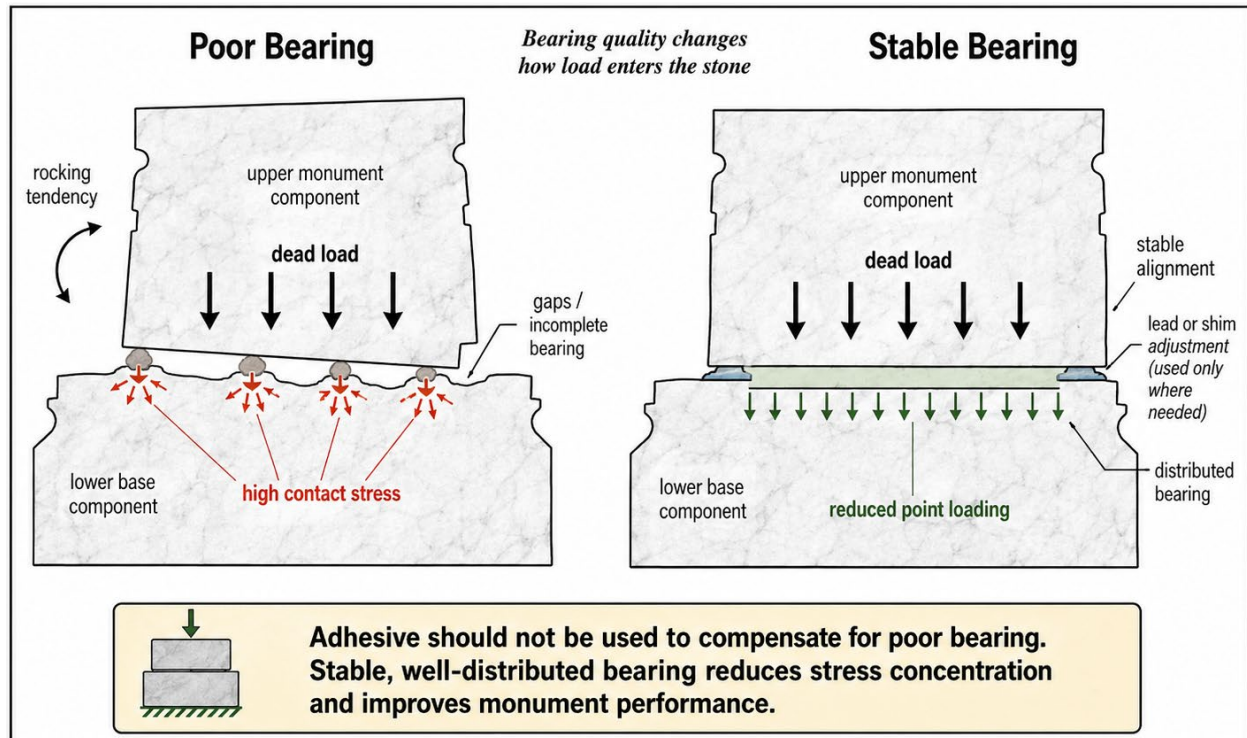
Lead should therefore be understood as an **adjustment and local load-distribution material**, not as a substitute for appropriate bearing geometry.

This point is particularly important in the Gravestone Guardians system. The objective should not be to suspend a monument component on four pieces of lead while adhesive and setting compound fill the remaining void. The monument should possess a

fundamentally stable bearing relationship, with the lead used to refine level, spacing, and contact.

Figure 13.1 demonstrates why bearing quality should be resolved before adhesive restraint is introduced. Concentrated contact at isolated high points can create rocking and local stress, whereas properly adjusted bearing distributes compression more effectively and reduces the amount of structural work subsequently assigned to the adhesive.

Figure 13.1: Poor Bearing Versus Stable Bearing



Note. In poorly seated monument joints, dead load may be transferred through a few isolated high points, producing stress concentration, local instability, and rocking. In a properly seated joint, load is distributed more evenly through broad bearing, with lead or similar adjustment material used only to refine contact and alignment rather than to carry the entire structural load.

13.4. Lead Creep Under Sustained Compression

Lead's softness also creates one of its principal limitations.

Lead and lead alloys can undergo significant creep at room temperature when subjected to sustained compressive loading. Published materials research specifically documents compressive creep in lead alloys and notes that this time-dependent deformation can be substantial enough to be exploited deliberately in some masonry applications (Sahota & Riddington, 2000).

For monument conservation, creep means that a lead wedge should not be regarded as dimensionally immutable after installation. Under sufficient sustained pressure, the metal can continue to deform gradually.

This behavior can be beneficial in moderation because the lead conforms to the adjoining stone. Excessive reliance upon a very small lead bearing area, however, could permit long-term compression or extrusion of the shim and alter joint spacing.

The practical implication is consistent with the broader argument of this paper: lead works best as one component of a distributed bearing system.

A broad, heavy monument should not be balanced permanently upon several undersized pieces of lead. If the stone surfaces provide substantial bearing and the lead makes relatively small adjustments, limited creep is less likely to control the geometry of the entire assembly.

13.5. Wedge Thickness

Wedge thickness influences both adjustment capacity and joint geometry.

A very thin wedge provides only limited correction but keeps the monument components relatively close together. A thicker wedge creates greater adjustment capability while also increasing the width of the resulting joint.

Excessive joint width can create several problems. More setting material may be required, the exposed perimeter becomes more visually prominent, leverage can increase at the edge of the component, and the monument may increasingly appear to rest on isolated shims rather than on a broad support interface.

Some monument-preservation guidance recommends keeping lead spacers comparatively thin and positioning them near—but not directly at—the corners or fragile outermost edges. Cemetery Conservators for United Standards, for example, describes lead spacers as a means of maintaining joint space and assisting level adjustment while cautioning against excessive thickness (Cemetery Conservators for United Standards, n.d.).

The precise acceptable thickness depends upon the monument geometry and original joint, but the governing principle is straightforward: **a wedge should correct the interface, not redefine it.**

13.6. Placement Near Corners

Lead wedges are commonly positioned near the corners of rectangular monument components because widely spaced support points provide efficient control over level and rocking.

Four points define a stable plane more effectively than several closely grouped points, and adjustment at one corner allows the setter to correct local elevation without disturbing the entire interface.

Yet corner placement requires care. Historic marble can be weakest near exposed edges, particularly where corners are already chipped, sugared, fractured, or thin. Placing a highly concentrated bearing point immediately at such an edge may increase the risk of spalling.

A small setback from the outside edge generally allows the load to enter a larger surrounding volume of stone while keeping the wedge accessible enough for adjustment.

The ideal location therefore balances three considerations:

- sufficient separation among bearing points to control level;
- enough surrounding sound stone to carry the local load; and
- sufficient accessibility to permit placement and future understanding of the setting system.

This is a case in which a short field checklist may eventually be useful, but the mechanics are more important than prescribing one universal distance from an edge.

13.7. Lead and Localized Adhesive Pads

Lead wedges become particularly significant when used alongside localized adhesive because the two materials can divide structural responsibilities.

The lead establishes joint spacing and bearing. The adhesive provides supplemental restraint against relative movement. If the upper component is seated correctly, the adhesive is not required to prevent the stone from settling downward as the monument weight comes onto the joint.

This arrangement also prevents a practical problem associated with uncured adhesive: excessive squeeze-out.

If two heavy stone components are lowered directly together without controlled spacing, a low-viscosity adhesive or soft putty can be displaced from the joint. Wedges maintain a minimum interface while the adhesive cures.

The important distinction is that maintaining adhesive thickness is a secondary benefit. The lead's first structural purpose remains control of the bearing geometry.

This relationship is evident in contemporary preservation and monument-setting practice, where lead wedges, setting compound, and adhesive are often used together rather than as competing materials (Atlas Preservation, n.d.-a; Town of Nantucket, 2022).

13.8. Lead Versus Plastic Shims

Modern plastic shims provide several obvious practical advantages. They are inexpensive, corrosion resistant, easy to obtain, dimensionally consistent, and free from the occupational health concerns associated with lead.

Their mechanical behavior, however, differs from soft lead.

Many rigid plastics do not deform around stone asperities as readily. Depending upon formulation, they may also creep substantially under sustained load, become brittle with aging, or respond differently to temperature. Manufacturer-specific properties would therefore need to be considered rather than treating “plastic” as a single material.

Plastic also introduces an organic polymer bearing surface that may behave differently from the mineral and metallic materials traditionally present in monument joints.

These observations do not justify a categorical prohibition. A well-characterized engineered polymer shim may perform acceptably in some circumstances.

The question is whether it offers a conservation advantage sufficient to replace a material whose field behavior in monument setting is already well understood.

At present, lead remains attractive where thin, conformable adjustment is required, provided it is handled safely and not asked to carry the entire monument on isolated points.

13.9. Lead Versus Steel and Other Hard Metals

Steel and stainless steel provide very different bearing behavior.

Their stiffness and hardness make them valuable as structural pins, anchors, and reinforcement when high mechanical capacity is required. The same properties are less attractive when the objective is simply to accommodate small irregularities beneath weathered marble.

A thin steel shim will not conform to the stone in the manner of lead. If contact occurs at only a few microscopic high points, loads remain locally concentrated.

Steel may also create staining or corrosion concerns if an inappropriate alloy is used. Stainless steel substantially reduces corrosion risk and remains the preferred metallic reinforcement in many architectural conservation contexts; GSA specifications for stone dutchman repairs, for example, identify stainless steel for pins and anchors (U.S. General Services Administration, 2026).

That suitability for reinforcement does not make stainless steel an optimal general-purpose bearing shim.

Bearing and reinforcement are different functions.

13.10. Stone Shims

Small pieces of compatible stone represent another possible bearing material.

Their chemical and thermal compatibility can be excellent, and properly selected stone is not vulnerable to metallic corrosion. Historically, stone chips and fragments have been used within masonry setting beds. The limitation is hardness.

A stone shim placed between two marble surfaces cannot deform appreciably. Its geometry therefore has to be correct before load is applied. An irregular chip can create point contact more severe than the defect it was intended to correct.

Stone shims are most defensible when they are relatively broad, flat, and intentionally shaped rather than improvised from sharp fragments.

They may be particularly appropriate when incorporated into a mineral mortar bed where the surrounding mortar helps distribute load.

13.11. Wood Wedges

Wood is extremely useful during the process of monument setting but is generally less attractive as a permanent bearing material.

Temporary wooden wedges, cribbing, blocking, and softening allow components to be raised, aligned, and manipulated safely before final placement. Their low hardness reduces the risk of chipping stone during adjustment.

Long-term burial within a monument joint introduces different concerns. Wood absorbs and releases moisture, changes dimension, degrades biologically, and eventually loses structural capacity. A joint dependent on permanent wooden shims would therefore change as the wood ages.

Wood should ordinarily remain a **temporary setting aid**, removed before the monument reaches its final bearing condition.

This distinction between temporary and permanent support should be documented clearly in treatment procedures.

13.12. Elastomeric Bearing Materials

Rubber and engineered elastomeric pads can accommodate irregularities and distribute load effectively in modern construction. They are intentionally used in structural bearings precisely because they can deform while carrying substantial compression.

For historic cemetery monuments, however, several questions arise. Elastomers can creep, harden, soften, swell, or lose additives over long exposure periods. Their ultraviolet and ozone resistance varies. Some may stain porous stone or introduce unknown long-term interactions.

A thick elastomeric pad can also permit more movement than desirable beneath a tall monument component.

These materials should therefore be considered specialized options rather than default substitutes for lead.

Their potential is nevertheless worthy of experimental consideration. A thin, stable, nonstaining engineered elastomer could theoretically provide excellent stress distribution and accommodate differential movement. If long-term aging data demonstrated compatibility, it might offer a lead-free alternative in circumstances where occupational or environmental concerns favor avoiding lead.

At present, that possibility remains a research question.

13.13. Lead and Occupational Safety

The continued usefulness of lead does not remove its well-established health hazards.

Lead should be handled with appropriate gloves, good hygiene, controlled cutting practices, and measures that prevent ingestion or transfer of lead contamination to food, vehicles, clothing, and personal spaces. Waste and offcuts should be managed appropriately.

The quantities involved in monument wedges may be small, but occupational exposure is cumulative. Preservation practice should not romanticize a traditional material in ways that ignore modern health knowledge.

This consideration may ultimately encourage research into alternative conformable bearing materials.

For the present paper, however, occupational risk and conservation performance should remain analytically distinct. Lead may be mechanically well suited to a particular treatment while still requiring appropriate health controls.

13.14. Bearing Failure Modes

Bearing systems can fail even when adhesive remains intact.

Potential failure modes include gradual lead compression, extrusion of a wedge toward the joint edge, fracture of marble beneath a concentrated shim, crushing of weakened grains, migration of a poorly restrained wedge, loss of support following foundation movement, and rocking caused by uneven bearing.

These failures reinforce why monitoring should include more than the adhesive seam.

Changes in joint width, opening at one edge, local crushing, extrusion of bearing material, or newly developing tilt may indicate that the load path is changing beneath an otherwise intact bond.

A monument can therefore appear “well glued” while the support system beneath the adhesive is deteriorating.

The distinction is important for both diagnosis and retreatment.

13.15. Bearing Materials Within the Failure Hierarchy

Lead wedges and other bearing materials occupy a useful position within the failure hierarchy because they can be comparatively accessible and replaceable.

If a monument must be dismantled in the future, exposed joint material can be removed and the upper component lifted. Lead wedges can generally be identified and replaced without removing original marble. Their presence does not permanently couple large stone surfaces in the manner of a continuous structural adhesive. This makes them particularly compatible with the limited-bond philosophy.

Their sacrificial character should nevertheless not be overstated. A lead wedge is not deliberately expected to collapse under ordinary overload, and excessive deformation can destabilize a monument. Its conservation advantage lies principally in **adjustability and replacement**, not intentional mechanical failure.

13.16. Conservation Implications for Bearing Materials

For multi-piece historic marble monuments, stable bearing should be established before adhesive strategy is considered.

Thin lead wedges remain a defensible material for fine adjustment, level control, joint spacing, and local distribution of contact stresses. Their softness and established monument-setting history provide advantages that rigid shims do not automatically reproduce. Contemporary conservation specifications document their continued use alongside bonding agents and monument setting compounds (Cemetery Conservators for United Standards, n.d.; Town of Nantucket, 2022).

Their limitations should be equally explicit. Lead creeps under sustained compression, should not carry excessive load through isolated small areas, requires occupational precautions, and cannot correct fundamentally defective bearing surfaces.

The Gravestone Guardians limited-bond system is therefore most defensible when the lead wedges remain **subordinate components within a broad, stable bearing interface**.

Their function is to help the stone sit correctly.

They should not become the only things the stone is sitting on.

14. Monument Setting Compounds and Perimeter Joint Materials

14.1. A Perimeter Joint Is Not Necessarily an Adhesive Joint

Once a multi-piece monument has been aligned, brought into stable bearing, and restrained as necessary, an exposed joint remains between the components.

That joint must contend with rain, dirt, biological growth, insects, freeze-thaw cycling, temperature changes, and repeated wetting and drying. The temptation is to fill the visible opening with whatever structural adhesive has already been used inside the joint.

Doing so combines two different functions.

Structural adhesive transfers meaningful load between the stones. Perimeter joint material primarily protects and closes the exposed interface. It may provide some supplemental restraint, but it should not necessarily be relied upon as the principal structural connection.

Keeping those functions separate improves both maintenance and retreatability.

A deteriorated perimeter joint should ideally be renewable without dismantling the monument or cutting through a permanent structural adhesive.

14.2. Monument Setting Compound

Commercial monument setting compounds were developed specifically for setting stone monuments and creating durable joints between monument components.

Products vary by manufacturer, but traditional setting compounds are generally nonhardening or semi-hardening oil- or putty-like materials rather than rigid structural epoxies. They are intended to remain workable enough to accommodate the practical irregularities associated with stone setting while providing a weather-resistant seal.

Contemporary cemetery conservation specifications and monument-setting resources continue to document these materials. The Town of Nantucket's Old North Cemetery specification calls for detached markers to be reset with bonding agent, lead wedges, and monument setting compound, while Atlas Preservation documents a flat-base repair system combining monument setting compound, Pratley Standard Setting Putty, and lead wedge (Atlas Preservation, n.d.-a; Town of Nantucket, 2022).

These references are significant because they demonstrate the functional separation central to the present paper: setting compound, adhesive, and lead are supplied as different materials because they perform different jobs.

14.3. Setting Compound as Weather Joint

The primary conservation value of monument setting compound lies in its ability to close the perimeter without converting the visible joint into a rigid mineral or polymer seam.

A comparatively yielding compound can follow small changes in joint geometry better than a hard epoxy. If minor movement occurs, the compound may deform or separate locally rather than transmitting the entire displacement into the stone.

This does not mean setting compound should be considered mechanically neutral. A continuous bead provides some adhesion and shear resistance, and the magnitude of that contribution varies by product.

Its structural contribution should nevertheless remain secondary in the limited-bond model.

If failure of the setting compound alone would cause the monument component to become immediately unstable, the system is relying upon the perimeter material for more than weather protection.

14.4. Maintainability

Setting compound has an important advantage that rarely appears in strength comparisons: it can function as a **maintenance material**.

Exterior joints inevitably age. A material exposed at the perimeter may crack, dry, harden, lose adhesion, collect biological growth, or be disturbed mechanically. If that material can be removed locally and replaced without disturbing the concealed structural system, the monument becomes easier to maintain.

This approach resembles traditional masonry maintenance, where exposed mortar joints are periodically renewed while the principal stones remain intact.

The analogy should not be pushed too far because monument setting compound is chemically and mechanically different from mortar. The conceptual similarity lies in treating the exposed joint as renewable rather than expecting one application to remain permanent indefinitely.

A repair philosophy that anticipates maintenance is more realistic than one that defines success as never needing to touch the monument again.

14.5. Setting Compound and Retreatability

Perimeter compound can also influence the practical retreatability of a monument.

Before a stacked monument can be dismantled, the perimeter joint generally needs to be opened. A relatively accessible setting compound can be cut or removed while leaving the historic stone surfaces substantially intact.

Once the perimeter is open, lifting equipment can potentially separate the components and expose the internal bearing and restraint system.

A perimeter filled with rigid structural epoxy creates a very different condition. Mechanical cutting may be required before any movement is possible, and the polymer may be strongly attached to exposed marble edges.

The choice of perimeter material therefore directly affects future treatment even if the compound carries little structural load.

This is a clear example of system-level sacrificiability: a comparatively replaceable exterior layer preserves access to the more permanent internal components.

14.6. Oil-Based Compounds and Conservation Concerns

Traditional oil-based monument compounds are not without criticism.

Organic oils and plasticizing constituents may migrate into porous stone, producing staining or darkening. Different formulations can harden or embrittle with age. Product composition may not always be disclosed in the detail desirable for conservation evaluation.

Some preservation practitioners consequently favor lime-based mortar rather than commercial monument compound at historic joints. Contemporary cemetery-conservation guidance documents this disagreement, noting that some practitioners avoid oil-based compounds and rely instead on natural hydraulic lime setting materials (Cemetery Conservators for United Standards, n.d.).

This debate should not be reduced to traditionalists versus modernists.

An oil-based compound may provide excellent flexibility and ease of future removal while posing greater staining risk. Lime mortar may offer better mineral compatibility and documented composition while becoming harder, more brittle, or less tolerant of movement depending upon formulation.

The appropriate choice depends upon the stone, original joint design, exposure, and intended structural role.

14.7. Lime Mortar as a Perimeter Material

Lime-based mortar provides a compelling alternative where the joint was historically mortared or where a mineral perimeter is considered desirable.

Properly formulated lime mortar can remain comparatively porous, sacrificial, and repairable. It can be colored and textured to harmonize with the historic stone, and its weathering behavior is generally well understood.

National cemetery conservation work documented by the National Park Service includes repointing with mortar or lead depending upon the monument's original construction, illustrating that perimeter treatment should respond to the historical joint rather than impose a universal material (National Park Service, n.d.-d).

The principal limitation of mortar is rigidity relative to nonhardening setting compound. Even comparatively soft lime mortar becomes a solid mineral material. If the monument components move relative to one another, the mortar will crack rather than deform indefinitely.

This may be acceptable—and even desirable—if the mortar functions sacrificially and can be repointed readily.

What should be avoided is an unnecessarily strong mortar that converts slight monument movement into edge loss.

14.8. NHL 3.5 and NHL 5

Natural hydraulic lime is frequently proposed for monument setting because it develops hydraulic set while retaining characteristics closer to traditional masonry than Portland-cement-rich mortar.

Different NHL classifications develop different mechanical properties, and designation alone does not determine the properties of the finished mortar. Aggregate type, binder ratio, water content, joint thickness, curing, and environmental exposure all influence performance.

Preservation guidance for multi-piece monuments sometimes recommends NHL 3.5 or NHL 5 setting mixes, particularly where a ready-made hydraulic material simplifies field application (Cemetery Conservators for United Standards, n.d.).

Selection should nevertheless remain substrate-specific.

A relatively strong NHL mortar may be appropriate beneath large sound granite components while providing unnecessary stiffness against weathered marble. The weakest

mixture capable of reliably performing the intended joint function is generally the more conservation-oriented direction, provided durability remains adequate.

14.9. Lead Pointing

Historic monuments sometimes contain lead not merely as concealed wedges but as exposed joint material.

National cemetery conservation projects have documented original lead pointing and replacement using lead wool where continuation of the historic material was appropriate (National Park Service, n.d.-d).

Lead pointing behaves differently from both mortar and oil-based compound. Its malleability allows it to accommodate some movement, and it can form durable joints without the hydraulic curing requirements of mortar.

Where original evidence clearly demonstrates lead pointing, repair in kind may provide the strongest historical justification.

The technique requires appropriate workmanship and material knowledge and should not be introduced indiscriminately to monuments that were never constructed that way.

Historical compatibility includes respecting original construction, not merely choosing historically available materials.

14.10. Modern Elastomeric Sealants

Silicone, polyurethane, hybrid-polymer, and other elastomeric sealants are common in modern construction and occasionally appear in monument work.

Their flexibility can appear attractive. A well-designed elastomer can tolerate joint movement far beyond that accommodated by mortar and can remain water resistant for years.

Historic marble raises several concerns.

Some sealants can stain porous stone through plasticizer migration. Adhesion can be difficult to remove completely. Residual silicone contamination is particularly problematic because future adhesives and repair materials may bond poorly to surfaces contaminated with silicone oils.

Modern sealants also tend to create joints that look and age differently from traditional monument materials.

This does not make all elastomeric sealants inappropriate. Products specifically formulated and tested for natural stone may avoid some staining issues.

Their selection should nevertheless require a clear advantage over monument setting compound or compatible mortar rather than simply convenience or availability.

14.11. Hard Structural Epoxy as Perimeter Joint

Using structural epoxy at the exposed perimeter should generally be distinguished from using the same resin within a fracture.

At the perimeter of a multi-piece monument, the epoxy creates a hard band exactly where future movement becomes visible and accessible. Because edge regions are frequently important during rocking and overturning, this rigid ring can transmit substantial forces into relatively vulnerable marble.

It also complicates maintenance. Renewing the joint requires cutting or grinding permanent resin from historic stone.

A structural epoxy perimeter may therefore undermine two objectives simultaneously: it creates a highly restrained edge and removes the possibility of straightforward joint renewal.

Where epoxy has been selected for localized internal restraint, there is little reason to extend it unnecessarily to the exterior merely to create a neat finished seam.

The perimeter should be allowed to remain a different material layer.

14.12. Completely Sealing the Joint

It is tempting to assume that the ideal monument joint should be completely impermeable to water.

Exterior stone behavior is more complicated.

Preventing bulk rain entry into an open horizontal joint can clearly be beneficial. Water entering directly between monument sections can support biological growth, transport dirt and salts, and contribute to freeze-related deterioration.

At the same time, stone inevitably contains and exchanges moisture through other pathways. A completely impermeable joint can alter how water dries from the interface, particularly if moisture enters from the stone above, through cracks, or from the foundation.

The goal should therefore be **controlled water management**, not an abstract pursuit of absolute sealing.

Perimeter materials should reduce direct water entry while avoiding unnecessary broad impermeable coatings across historic stone surfaces.

This is another reason the limited-bond approach leaves much of the internal interface free from structural polymer.

14.13. The Joint as an Inspection Zone

A well-designed perimeter joint can provide information.

Opening, cracking, extrusion, staining, displacement, or changes in joint width may reveal settlement or movement before major stone failure occurs.

A highly rigid, permanently bonded joint may suppress these visible indicators until stress has accumulated elsewhere.

The concept parallels the earlier distinction between stabilizing movement and concealing movement.

A sacrificial or maintainable perimeter material can act as an early-warning element. Cracking does not automatically mean the monument is structurally failing; it may indicate that the joint is responding to movement and requires evaluation.

Repair documentation should therefore record the initial joint width and appearance so later changes can be interpreted.

14.14. Where Monument Setting Compound Fits in the GG System

Within the Gravestone Guardians approach, monument setting compound should be described principally as a **perimeter and joint-management material**, not as the primary structural adhesive. The sequence is important.

The base and monument component are stabilized and dry-fitted. Lead establishes final bearing and spacing. Localized Pratley Putty provides supplemental restraint where required. Setting compound closes the accessible perimeter and may contribute some secondary adhesion.

This functional description is stronger than claiming that every material is essential to every monument.

Some historically mortared monuments may be more appropriately reset using lime-based material. Some socketed tablets require mortar rather than monument compound. Some components may require mechanical reinforcement.

The GG system applies most coherently to flat-bearing multi-piece monuments where gravity already performs much of the structural work.

14.15. Conservation Implications for Perimeter Materials

The exposed joint should be designed as a maintainable component rather than as an extension of the permanent structural adhesive.

Monument setting compound offers practical advantages for flat-base monument reassembly because it accommodates small irregularities, assists weather closure, and can remain comparatively accessible. Contemporary monument-setting and preservation specifications demonstrate continued use alongside lead wedges and bonding agents (Atlas Preservation, n.d.-a; Town of Nantucket, 2022).

Lime-based mortars provide a strong alternative where historical construction, stone condition, or conservation philosophy favors a mineral sacrificial joint. Original lead pointing should be respected where present.

Rigid epoxy should generally remain confined to the structural role for which it was selected rather than being extended around the perimeter merely for convenience.

The perimeter joint is where future maintenance begins.

It should not be designed as though future maintenance will never be necessary.

15. Continuous Bonding Versus Limited-Bond Reassembly

15.1. Comparing Repair Systems Rather Than Adhesives

The preceding material chapters allow the central comparison of this paper to be made more precisely. The choice facing a conservator is rarely simply AKEPOX versus Pratley, epoxy versus mortar, or adhesive versus pin. Each material can be incorporated into multiple geometries that create substantially different structural systems. A high-strength adhesive used sparingly may produce less permanent alteration than a weaker adhesive spread across an entire historic interface. A mineral mortar can be sacrificial when used as exposed pointing yet excessively rigid when packed into a fragile fracture. A pin may be the most invasive local intervention while providing the least damaging overall system if a tall component cannot otherwise be stabilized safely. Treatment selection should therefore compare **complete repair configurations**.

For multi-piece monuments, five broad configurations provide a useful analytical framework:

System A — Continuous structural adhesive bonding

System B — Localized adhesive bonding

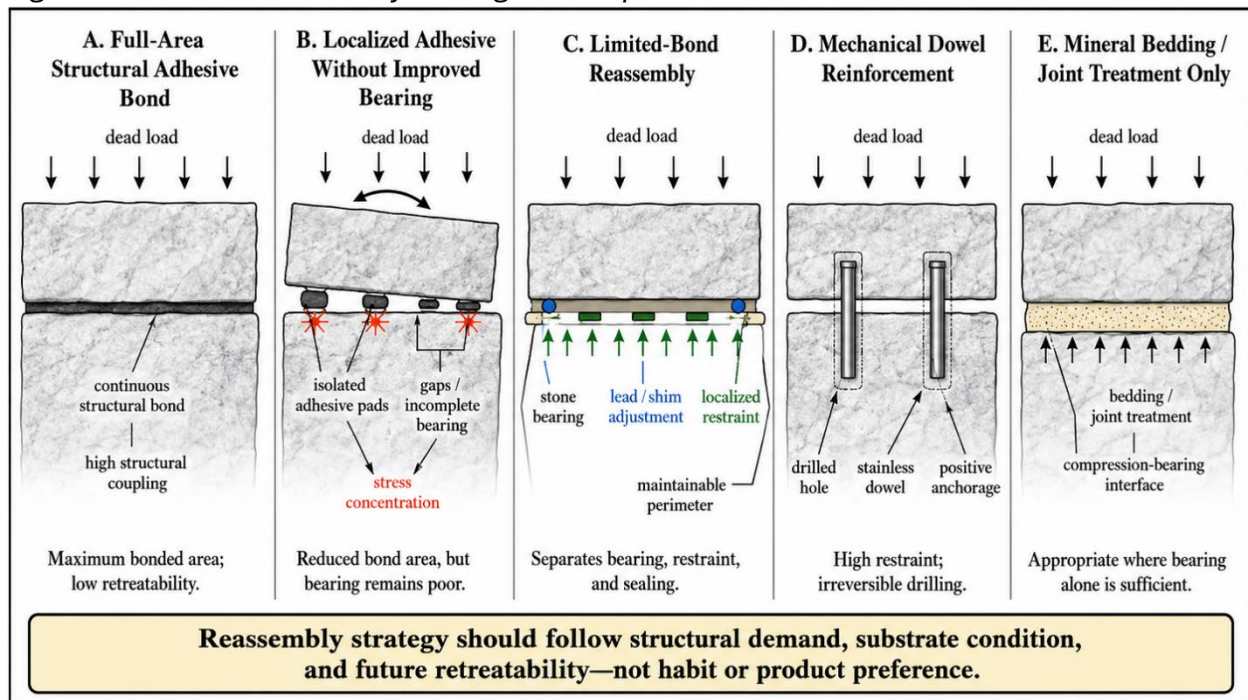
System C — Stable bearing + localized adhesive restraint + maintainable perimeter joint

System D — Mechanical reinforcement + bedding/setting material

System E — Mineral-only reassembly

These categories simplify real practice, but they allow the advantages and liabilities of each structural philosophy to be compared consistently.

Figure 15.1: Five Reassembly Strategies Compared



Note. The five strategies shown here are conceptual rather than prescriptive. Full-area bonding increases structural coupling and permanent bonded area; localized adhesive without improved bearing can leave stress concentrations unresolved; limited-bond reassembly attempts to separate bearing, restraint, and perimeter-joint functions; dowel reinforcement provides positive anchorage but requires irreversible drilling; and mineral bedding or joint treatment alone is appropriate only where structural demand remains low and stable compression-bearing support is already present.

15.2. System A — Continuous Structural Adhesive Bonding

In a continuous structural bond, most or nearly all of the available interface between monument components is coated with adhesive before assembly. The principal advantage is obvious: a large bonded area can provide substantial resistance to sliding, separation, overturning, and relative movement. Stress may be distributed over more surface than in a small localized connection, reducing some local stress concentrations under ordinary loading. The treatment can also be relatively straightforward operationally. When surfaces are sound and reasonably flat, the adhesive is mixed, distributed, the components are brought together, and alignment is maintained until cure. For commercial fabrication, these properties are highly desirable.

The conservation liabilities arise from the same geometry. Nearly the entire historic interface becomes permanently bonded. The large area can transmit substantial force into the marble if the monument experiences settlement, rocking, impact, or overturning.

Moisture transport through the interface can be altered over a broad region. Future dismantling may require progressive destruction of the adhesive or surrounding stone because access is limited primarily to the perimeter. The system effectively attempts to convert two monument components into a more monolithic unit. That objective may be appropriate in some structural conditions, but it should be adopted deliberately.

15.3. Strength Versus Consequence in Full Bonding

A continuous bond is frequently praised because it makes the monument extremely difficult to separate. That statement describes immediate mechanical performance, not necessarily conservation success. If a severe lateral force acts on the upper section, a strong full-area bond can prevent separation at the original interface. The force must then be resisted by the marble, the base, the next joint below, or the foundation. If one of those regions is weaker, failure simply moves. This phenomenon is not unique to adhesive. Every structural strengthening intervention changes the load path. The conservation question is whether moving that failure point produces a preferable outcome.

For a heavy architectural element above an occupied public area, preventing separation may clearly outweigh concerns about possible substrate damage during an extraordinary overload. For a low nineteenth-century cemetery die resting securely on a broad base, permanently coupling every square inch of the interface may offer much less additional benefit. The appropriate structural capacity is contextual.

15.4. System B — Localized Adhesive Bonding

Localized bonding reduces permanent adhesive area by applying resin or putty only at selected regions. The system preserves more of the original interface from direct polymer contact and can reduce the total amount of force transferred through adhesive. Future dismantling may also be more practical because separation can progress through unbonded regions before reaching the localized pads. The disadvantages arise from concentration. Each adhesive region must transfer a greater portion of the restraint load relative to its area. Poor placement can direct stress into fragile marble. Unknown pad size or irregular application can make performance less predictable. Where the stone lacks independent stable bearing, localized adhesive can become unintentionally responsible for support.

System B therefore becomes most defensible when paired with deliberate bearing design. Without that bearing, “using less epoxy” is not a repair philosophy. It is simply using less epoxy.

15.5. System C — Bearing + Localized Restraint + Maintainable Perimeter

System C represents the Gravestone Guardians limited-bond model in its most developed form. The monument component is first established in stable bearing. Lead wedges or another appropriate bearing system refine alignment and joint spacing. Localized structural adhesive or putty is positioned where supplemental restraint is needed. The exposed perimeter is then closed using monument setting compound, mortar, lead pointing, or another material selected for joint management rather than primary structural strength.

The essential feature is **functional separation**. The stone and bearing materials carry gravity. The adhesive resists displacement. The perimeter material manages exposure and maintenance. Because no single material is required to perform every function, each can be selected according to the role it performs best. This system embodies the concept of system-level sacrificiability developed in Chapter 3.

15.6. Evidence That the Combined System Exists in Preservation Practice

The combined use of lead wedges, bonding material, and monument setting compound is not unique to Gravestone Guardians. A municipal conservation specification for Nantucket's Old North Cemetery identifies resetting detached markers using a bonding agent, lead wedges, and monument setting compound. Commercial monument-preservation kits similarly combine Pratley Standard Setting Putty, lead wedge, and monument setting compound for flat-base monument reassembly. Such evidence should be interpreted correctly (Atlas Preservation, n.d.-a; Town of Nantucket, 2022). It establishes that the material combination is recognizable within monument-conservation practice. It does **not** establish experimentally that the system produces the least damaging failure hierarchy on weathered historic marble. The latter remains the research question of this paper. This distinction allows the GG practice to be taken seriously without presenting practitioner tradition as scientific validation.

15.7. Mechanical Logic of System C

Consider an upper marble die weighing several hundred pounds. Under ordinary conditions, gravity presses the die into the base. Properly positioned lead wedges maintain a small controlled joint and assist uniform bearing. Friction between the loaded surfaces provides inherent resistance to sliding. Localized Pratley pads add resistance to lateral

displacement and opening. The perimeter compound reduces direct environmental exposure. Under modest service loads, all of these components contribute.

Under an unusual overload, the behavior becomes more complex. Friction may be overcome first. Adhesive pads then carry increasing shear or tension. Perimeter material may deform or separate. If the load continues to rise, a pad may release, the substrate beneath it may fail, or the component may begin to move.

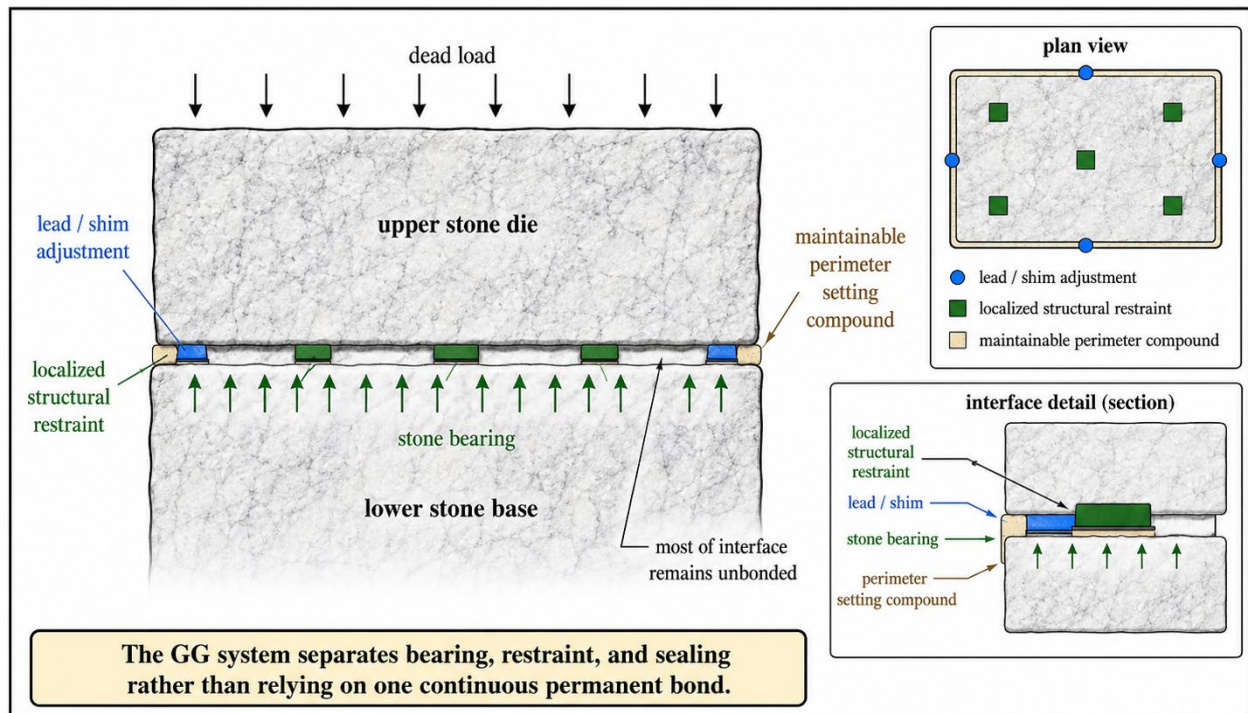
The design objective is to make those latter outcomes occur only beyond reasonably anticipated service conditions while avoiding a connection so extensive that extraordinary forces are transferred into a large volume of original marble.

This is the hypothesis that differentiates System C from both weak setting and full structural bonding.

The repair systems discussed in this chapter are compared conceptually in Figure 15.1. The comparison emphasizes that continuous bonding, localized bonding, bearing-supported limited bonding, mechanical reinforcement, and mineral-only reassembly differ not simply in material choice but in bonded area, load path, invasiveness, and likely retreatment burden.

Figure 15.2 illustrates the limited-bond reassembly model developed in this paper. Stable bearing remains responsible for primary compression, lead provides controlled adjustment, discrete adhesive locations supply supplemental restraint, and the perimeter joint remains a separate maintenance element, leaving much of the historic interface free of permanent adhesive.

Figure 15.2: Limited-Bond Reassembly System



Note. This conceptual diagram illustrates the limited-bond approach for broad, compression-loaded multi-piece monuments. Dead load is carried primarily through stable stone bearing; lead or shim elements refine alignment and support; localized restraint provides supplemental structural connection; and a maintainable perimeter setting compound closes and protects the outer joint without converting the full interface into one continuous permanent bond. The system is intended for conditions where bearing can be restored, and full-surface bonding or dowel reinforcement is not structurally necessary.

15.8. System-Level Sacrificiability in Practice

System C is not sacrificial because Pratley Putty is weak. It almost certainly should not be described that way without supporting mechanical data. Its sacrificial character instead arises through multiple layers. The exposed setting compound can age and be replaced. Lead can be adjusted or renewed during future dismantling. Large portions of the historic interface remain free from permanent structural polymer. Localized adhesive can potentially be accessed from surrounding unbonded areas. No new stone is removed through drilling where mechanical reinforcement is unnecessary.

This hierarchy can preserve more future options even if the adhesive pads themselves remain extremely strong. That is the central conceptual advance of the limited-bond model.

15.9. Limitations of System C

The system also has important limitations. It depends upon adequate inherent stability. A monument whose geometry produces substantial overturning demand may require more restraint than a few localized adhesive pads can reliably provide. It depends upon sound marble at the pad locations. Highly sugared or microcracked stone may fail locally. It depends upon competent bearing. If the stone is actually suspended on lead wedges and putty rather than broadly supported, the system's mechanics differ from the intended model.

It depends upon workmanship. Pad locations and quantities must be controlled rather than improvised during placement. It depends upon documentation. Once the monument is assembled, the adhesive becomes invisible. Finally, it depends upon performance that has not yet been fully quantified through controlled testing. The system should therefore be described as a **reasoned conservation approach requiring experimental validation**, not as a universally proven standard.

15.10. System D — Mechanical Reinforcement + Bedding Material

Mechanical reinforcement uses pins, dowels, anchors, cramps, or related components to transmit force across a joint. The great advantage is positive restraint. A properly designed pin can resist shear and tensile separation even after gravity and friction no longer contribute significantly. Mechanical reinforcement is therefore particularly valuable where geometry creates high overturning demand or where failure of the joint would create unacceptable danger. Architectural conservation specifications routinely employ stainless steel pins and anchors where replacement stone or structural attachment requires positive mechanical connection (U.S. General Services Administration, 2026). The conservation cost is concentrated invasion of the substrate.

Drilling removes original material permanently. The pin introduces a much stiffer component into the marble, and loads are transferred through the region surrounding the hole. Adhesive is normally still required to set the pin, meaning pinning does not necessarily eliminate polymer from the repair. A pin is therefore not a reversible alternative to adhesive. It is a different form of permanent intervention.

15.11. Pin Material and Stiffness

Research into pinning materials for marble sculpture demonstrates how mechanically complex this intervention can be. Riccardelli, Wheeler, and colleagues examined pin materials with moduli ranging from approximately 0.5 to 197 GPa specifically because conventional stainless-steel pins are much stiffer than marble. Their work questioned the

assumption that traditional stainless steel is automatically the optimal reinforcement for every marble repair and explored how pin stiffness influences joint behavior (Riccardelli et al., 2010). This evidence reinforces the argument made throughout both Technical Papers No. 2 and No. 3. A material can be durable, familiar, and exceptionally strong while still introducing mechanical mismatch. The relevant question is whether the mismatch is necessary to provide the required structural function.

15.12. System E — Mineral-Only Reassembly

Mineral-only systems avoid synthetic structural adhesive and instead rely upon stone geometry, gravity, mortar, grout, lead, or related traditional materials. This approach can provide exceptional retreatability and material compatibility where the monument is inherently stable. A broad die resting securely on a base may require little more than proper bearing and a historically appropriate joint material if sliding and overturning risks are negligible.

The system becomes less adequate as tensile restraint increases. Soft mortar that performs beautifully as sacrificial bedding cannot prevent a tall narrow upper component from overturning under significant lateral load. Increasing mortar strength enough to perform that structural role may undermine the very sacrificiality that motivated the mineral-only approach. The conservation virtue of mineral systems therefore depends upon not requiring them to imitate high-strength adhesives.

15.13. Comparing the Five Systems

The principal differences can be summarized as follows:

Table 15.1: Comparison of Five Monument Reassembly Systems

Characteristic	Full adhesive bond	Localized adhesive	Bearing + localized restraint	Mechanical reinforcement	Mineral-only
Permanent bonded area	High	Low–moderate	Low	Low at interface, concentrated at holes	Low
Original stone removed	Usually none	Usually none	Usually none	Yes, through drilling	Usually none
Tensile restraint	High	Moderate/variable	Moderate/variable	Potentially very high	Low
Shear restraint	High	Moderate	Friction + localized adhesive	High	Primarily friction/mortar
Dependence on stable bearing	Moderate	High	Very high	Moderate	Very high
Future dismantling	Difficult	Potentially moderate	Potentially favorable	Difficult around pins	Generally favorable
Potential cohesive stone failure	High if bond exceeds substrate	Localized	Localized by design	Concentrated around reinforcement	Generally lower but formulation-dependent
Moisture alteration across interface	Potentially extensive	Limited	Limited	Usually limited	Often comparatively compatible
Best candidate	Where broad structural coupling is genuinely required	Stable components needing modest restraint	Broad, compression-loaded multi-piece monuments	Tall/high-load/safety-critical elements	Inherently stable historically mineral-set assemblies

Note. This table intentionally avoids assigning universal rankings. A treatment becomes appropriate only when its structural capacity is matched to the monument's actual demand.

15.14. The Principle of Sufficient Restraint

A useful decision criterion emerges from this comparison: **The preferred repair is the least invasive system that provides sufficient—not maximum—restraint for foreseeable service conditions.** This wording is important. “Least invasive” without “sufficient” can produce unstable repairs. “Sufficient” without “least invasive” can justify unnecessary drilling, bonding, or rigidification. The two concepts must remain together.

For a low, broad marble die, System C may satisfy both requirements. For a tall obelisk section with high overturning consequences, System D may be the less damaging adequate system despite its greater local invasiveness. For a stable low component with no meaningful movement history, System E may be entirely sufficient. Treatment selection should become progressively more invasive only as the structural problem requires it.

15.15. Failure Consequence as a Selection Criterion

The same load capacity can have very different conservation consequences depending upon how the system fails. Imagine three hypothetical repairs subjected to increasing overturning force. A fully bonded epoxy interface remains intact until a large section of marble spalls from the base. A limited-bond system releases one or more localized pads and produces small, repairable surface losses. A weak mineral system releases cleanly but allows the upper component to fall and shatter.

Ranking these repairs solely according to strength would favor the first. Ranking them solely according to sacrificial failure would favor the third. Conservation requires considering both **failure load and failure consequence**. The desirable system is the one that remains stable through foreseeable service while producing the least destructive plausible outcome beyond that range. This is the mechanical meaning of failure hierarchy.

15.16. Experimental Validation of the Systems

The proposed research program should compare complete system geometries rather than merely adhesive coupons. Small-scale stone specimens can examine material behavior, but mock monument interfaces are needed to evaluate the actual GG hypothesis. Candidate assemblies should include full-area epoxy, localized epoxy or Pratley, lead-supported limited-bond systems, B-72 intervention-layer variants, and mineral setting systems. Loads should include shear, eccentric loading, and progressive overturning rather than only direct tension.

The most informative observations would include:

- the load at first measurable movement;

- displacement before failure;
- stiffness;
- failure location;
- amount and depth of marble loss;
- whether adhesive remains removable or accessible;
- effect of repeated wet-dry and freeze-thaw exposure; and
- behavior after sustained loading.

The objective should not be to prove the GG method stronger than full epoxy bonding. It almost certainly will not be. The more meaningful objective is to determine whether it provides **adequate service capacity with a less destructive failure consequence**. That would constitute a genuine conservation advantage.

16. Pinning Versus Adhesive Reassembly Revisited

16.1. The Question Changes After Technical Paper No. 2

Technical Paper No. 2 examined one of the most persistent debates in historic monument repair: whether a broken or dismantled stone should be pinned or bonded using adhesive alone.

The analysis demonstrated that pinning should not be treated as an automatic structural upgrade. Drilling is invasive, removes original stone, introduces concentrated load-transfer zones, and can create destructive failure modes when reinforcement is poorly located or when the surrounding stone lacks sufficient integrity.

At the same time, epoxy should not be presented as a universally superior alternative. A rigid permanent bond can transfer failure into historic marble, and adhesive-only repair may provide inadequate reinforcement where significant bending, shear, overturning, or public-safety loads are present.

Technical Paper No. 3 adds another dimension. The relevant comparison is no longer simply **pin versus adhesive**. It is: **Which combination of bearing, restraint, adhesive, reinforcement, and joint material produces adequate stability with the least destructive foreseeable failure hierarchy?** That reframing changes the treatment decision substantially.

16.2. Why Pinning Became Associated with Professional Repair

Mechanical reinforcement has an intuitive appeal. A broken stone joined with adhesive can appear to rely upon “glue,” while a repair containing a stainless-steel or fiberglass dowel appears visibly—at least conceptually—to contain structural reinforcement. This perception can lead to the assumption that pinning is inherently more professional, durable, or conservative. Engineering reality is more nuanced. A pin transfers load only through the stone surrounding the drilled holes and through whatever adhesive or grout secures the pin. If the stone is weak, the reinforcement does not eliminate weakness; it concentrates structural demand around a smaller volume of marble. Pinning can therefore be excellent engineering when the stone and geometry support its use. It can also be unnecessary intervention when the joint is already stable through other means. Professional practice should be defined by diagnosis rather than by the presence of hardware.

16.3. Drilling as Irreversible Material Removal

The conservation consequence of drilling should be stated plainly. A drilled hole permanently removes historic stone. Unlike a surface adhesive that may be partly mechanically removed, the cylindrical volume extracted by the drill can never be returned in its original condition. Filling the hole later does not restore the removed marble. This does not make drilling unethical. Conservation regularly accepts permanent material removal where necessary. It does mean that pinning cannot be defended merely by criticizing epoxy for irreversibility. Both treatments are irreversible in different ways. The appropriate comparison is therefore **extent and consequence of irreversible intervention**.

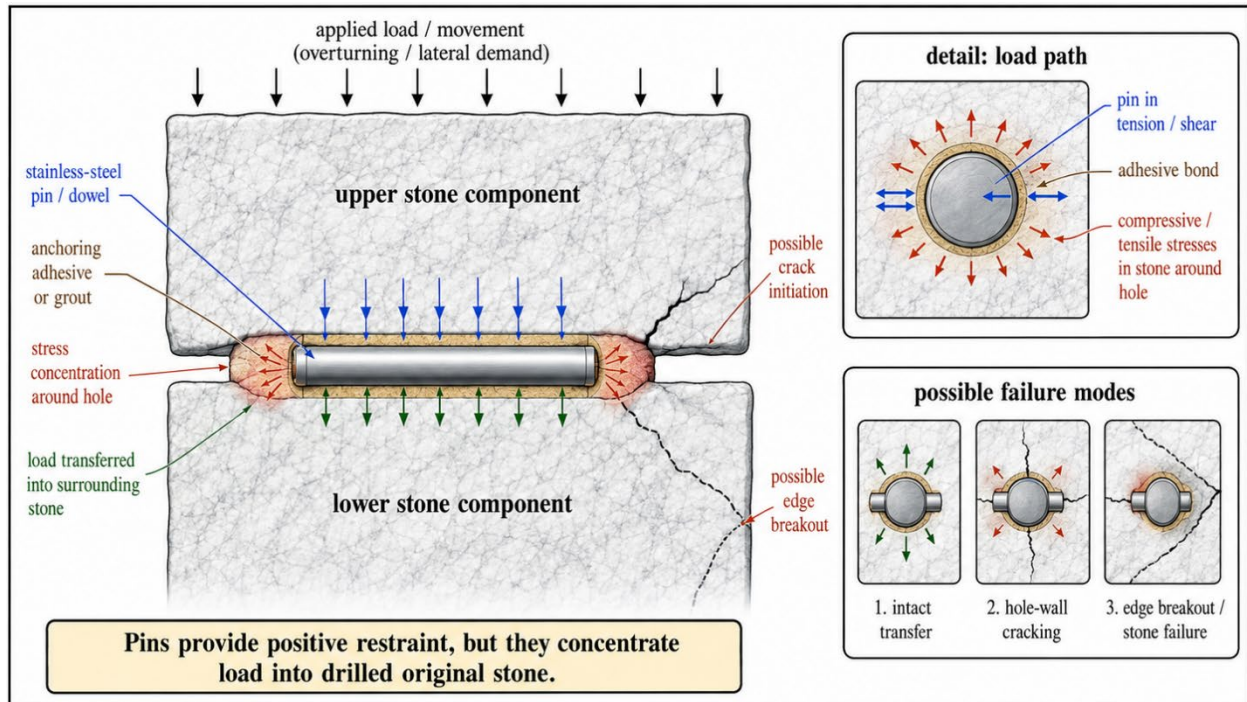
A few carefully located drill holes may be justified to prevent catastrophic failure of a tall monument. The same holes may be difficult to justify in a low, stable component that requires only modest protection against sliding.

16.4. Pins Create a New Load Path

Without a pin, force crosses a horizontal monument joint through compression, friction, adhesive, mortar, or other interface materials. With a pin, force can bypass portions of that interface and travel directly through the reinforcement. This can increase capacity dramatically. It also concentrates stress. The pin must transfer force into the adhesive surrounding it, which transfers force into the wall of the drilled hole. The marble around that hole therefore becomes part of the anchorage system. If the pin is extremely stiff relative to the stone, small movements can produce high localized stresses. The marble can crack from the hole, split along a weak plane, or break out around the end of the anchorage. Research into marble pinning materials specifically recognizes modulus mismatch as an important concern. Stainless steel remains widely used because of its corrosion resistance and strength, but its elastic modulus greatly exceeds that of marble, prompting investigation of alternative pin materials with lower stiffness (Riccardelli et al., 2010). A stronger pin is not necessarily a safer pin if the surrounding stone becomes the sacrificial component.

The resulting change in load path is illustrated in Figure 16.1. A pin or dowel can provide effective positive restraint, but the force carried by the reinforcement must ultimately be transferred into the walls of drilled historic stone, creating localized stresses whose acceptability depends upon stone condition, geometry, edge distance, embedment, and reinforcement stiffness.

Figure 16.1: Pin/Dowel Load Transfer and Stress Concentration



Note. This conceptual diagram illustrates how a pin or dowel provides positive mechanical restraint by transferring force across a joint through the reinforcement and into the surrounding stone. The system can be effective where structural demand requires reinforcement, but the drilled holes create concentrated load-transfer zone. If stone condition, edge distance, embedment depth, pin stiffness, or anchoring geometry are inadequate, stresses may produce cracking, localized breakout, or broader cohesive stone failure. The figure is conceptual and is intended to clarify load path and failure risk rather than represent a specific engineered calculation.

16.5. Pin Diameter

Pin diameter affects both capacity and invasiveness. A larger dowel can carry greater force and may provide a larger surface area for load transfer, but it requires removal of more original stone. The thicker hole also leaves less remaining marble around the reinforcement, particularly in thin tablets. A very small pin removes less material but may lack sufficient strength or create extremely concentrated load transfer. The appropriate diameter is therefore determined by the load, stone thickness, edge distance, material, and anchorage length. This is why rules prescribing pins based simply upon tablet thickness are mechanically incomplete. The question is not whether a two-inch marble tablet is thick enough to physically accept a certain drill bit. It is whether the remaining marble after drilling can transfer the intended load without creating a more destructive failure mode than the fracture being repaired.

16.6. Edge Distance and Stone Condition

Drilled holes require sufficient sound stone around them. A pin placed too near a thin edge can produce breakout. A hole intersecting a microcrack can extend it. Drilling into sugared or granular marble can damage the wall of the hole before the repair is even assembled. Weathered historic marble therefore deserves greater conservative margin than fresh structural stone. This is one reason pinning may become less appropriate precisely when the stone appears to need reinforcement most urgently. Severe deterioration reduces the material available to anchor that reinforcement. In such cases, alternative external support, broader bearing, limited adhesive, reduced loading, or acceptance that the fragment cannot safely be returned to service may be more responsible than drilling into an inadequate substrate.

16.7. Pins in Tablet Repairs

A transverse break through a thin tablet presents a particularly difficult decision. The repaired section experiences bending, making structural reinforcement conceptually attractive. A pin can bridge the fracture and provide tensile capacity independent of the adhesive surface. Yet the tablet's thin cross-section leaves limited room for drilling. Even small alignment errors can emerge through the face or edge. The hole removes significant material relative to the total section, and the pin may create a highly stiff inclusion through the repaired zone. An adhesive-only repair preserves the full remaining cross-section but relies entirely upon the adhesive-stone interface to transmit bending. Neither solution is inherently conservative.

For a sound, close-fitting fracture in a relatively low tablet with manageable service loads, a thin AKEPOX 5010 joint may represent the less invasive treatment. For a larger, highly loaded, repeatedly fractured, or geometrically unfavorable tablet, carefully designed reinforcement may become justified. The decision should follow the failure mechanics, not a blanket doctrine that every repaired tablet requires dowels.

16.8. Pins in Multi-Piece Monument Reassembly

Horizontal multi-piece monument interfaces present a different problem. Where a broad die already possesses substantial gravitational stability, a pin may contribute little during ordinary compression. Its value becomes apparent primarily during sliding, rocking, uplift, or overturning. The question is therefore how much resistance to those movements is needed. A tall, narrow monument component may benefit greatly from positive mechanical restraint. A low broad component may already resist movement through mass, friction, and geometry. Installing the same pinning system in both monuments simply

because both consist of a die sitting on a base ignores their different load paths. This is where the limited-bond model offers a credible alternative for the lower-risk assembly.

Lead establishes bearing. Localized Pratley or another adhesive provides supplemental restraint. Setting compound manages the perimeter. No historic stone is drilled. The system should not be expected to match the ultimate overturning resistance of stainless-steel reinforcement. It need only provide the capacity actually required.

16.9. When Pinning Is Clearly Appropriate

There are situations in which pinning or other mechanical reinforcement is difficult to avoid responsibly. These may include tall or slender components with significant overturning potential; projecting elements whose failure would result in a fall; monument sections with inadequate gravity-based stability; historically pinned assemblies where compatible replacement of failed reinforcement is appropriate; heavy sculptural elements whose adhesive joint would otherwise carry sustained tension; and installations where public safety requires positive mechanical attachment. Architectural stone practice reflects this distinction. GSA conservation procedures for stone dutchman repairs require mechanical attachments such as stainless-steel pins or anchors in addition to appropriate adhesives and mortars where replacement stone requires positive structural attachment (U.S. General Services Administration, 2026). The principle is not that all historic stone should therefore be pinned. It is that **mechanical attachment becomes appropriate when the load cannot responsibly be left to adhesion, gravity, or friction alone.**

16.10. When Pinning Should Be Avoided or Questioned

Pinning deserves greater skepticism where it is introduced primarily because it appears stronger. Conditions warranting caution include severely deteriorated marble, insufficient edge distance, thin tablets, uncertain drilling path, complicated internal cracking, small fragments that do not possess enough sound stone for an anchorage, and monuments whose geometry already provides adequate stability. Pinning should also be questioned when the justification is simply that an adhesive bond might eventually fail. Every repair can eventually fail. The relevant question is whether pinning changes that failure into something less damaging.

If a future overload that would have separated an adhesive pad instead causes a pin to break a large section of marble from the monument, the reinforcement has improved strength while worsening failure consequence. That tradeoff may be justified in a safety-critical monument. It should not be accepted automatically.

16.11. Adhesive Is Still Part of Most Pinning Systems

The apparent distinction between “pinning” and “adhesive repair” is also somewhat artificial because most modern dowel repairs use adhesive or grout to secure the pin within the drilled holes. Epoxy commonly fills the annular space around stainless-steel or composite pins. The repair therefore contains both mechanical reinforcement and permanent adhesive. This means the conservative argument for pinning cannot be that it avoids epoxy. Rather, pinning changes the geometry through which the adhesive and stone carry load. A relatively small volume of epoxy may be concentrated deeply within drilled holes rather than spread across the fracture interface. That can be advantageous when positive anchorage is required. It can also make retreatment exceptionally difficult because the cured resin and reinforcement are buried within the original stone.

16.12. Stainless Steel

Stainless steel remains a common pinning material because it combines high strength, stiffness, availability, predictable engineering properties, and excellent corrosion resistance when the appropriate grade is used. Its durability is important. Historic iron cramps and pins have caused extensive damage to stone when corrosion products expanded and split surrounding material. Stainless steel greatly reduces that risk. Its principal mechanical limitation is stiffness mismatch. With an elastic modulus far higher than marble, stainless steel changes relatively little dimension under loads that may deform or microcrack the surrounding stone. This can concentrate force at the anchorage. That mismatch does not invalidate stainless steel. It reinforces the need to use the minimum reinforcement required and to provide adequate embedment within sound stone.

16.13. Fiberglass and Composite Pins

Fiber-reinforced polymer rods offer lower density, corrosion resistance, and potentially different stiffness characteristics from metal. They are attractive partly because they avoid metallic corrosion and can sometimes be selected with modulus closer to stone. Their behavior depends strongly upon fiber type, orientation, resin matrix, diameter, and manufacturer. “Fiberglass” should therefore not be treated as one universal pin material. Long-term exterior aging, sustained-load creep, moisture exposure, ultraviolet effects at exposed ends, and compatibility with anchoring adhesive all require consideration. Composite pins may provide excellent options for some conservation repairs, but their selection should be evidence-based rather than founded on the general assumption that nonmetallic reinforcement is automatically gentler.

16.14. Retreatability of Pins

A pinned repair is sometimes described as reversible because the stone pieces could theoretically be separated by drilling out or cutting the pin. In practice, the degree of retreatability varies considerably. A stainless-steel pin deeply embedded in epoxy may be extremely difficult to remove without enlarging the original hole. Cutting the pin can leave permanent metal and adhesive inside both fragments. Drilling it out risks damaging surrounding marble. Composite pins may be easier to drill through but can still leave resin and fiber embedded in the stone. The meaningful comparison with localized adhesive should therefore consider what a future conservator actually has to remove. Several small surface adhesive pads may be chemically irreversible yet mechanically accessible after lifting the component. A theoretically removable pin may be deeply buried and practically impossible to extract without additional stone loss. Retreatability again depends upon geometry rather than material label alone.

16.15. Limited-Bond Reassembly as an Alternative to Routine Pinning

The strongest case for limited-bond reassembly lies not in replacing every pinned repair, but in reducing **routine pinning where the structural demand does not require it**. Many multi-piece monuments are stable primarily because of their mass and broad bearing surfaces. Their historic construction may have relied substantially upon gravity, setting materials, and limited mechanical connection. Where such a monument requires reassembly after displacement rather than reconstruction after structural fracture, drilling new holes should not automatically be the first response.

Stable bearing can be restored. Lead can establish controlled alignment. Localized adhesive can supplement sliding and separation resistance. The perimeter can remain maintainable. If those elements provide sufficient service capacity, the conservation advantage is straightforward: adequate stability has been achieved without removing additional original marble. This is the middle ground the present paper seeks to evaluate.

16.16. Limited Bonding Is Not “Pinning Without the Pins”

It is important not to describe localized adhesive as though it simply performs the same job as a dowel less invasively. It does not. A rigid pin crossing an interface provides positive mechanical restraint through a defined structural element. Localized putty provides adhesive restraint dependent upon surface cohesion and bonded area. Their capacities, deformation, and failure modes are different. A limited-bond system should therefore be selected only when positive mechanical reinforcement is unnecessary. Trying to replace a structurally required pin with several adhesive pads merely to avoid drilling would violate

the same minimum-intervention principle the method is intended to uphold. Minimum intervention means avoiding unnecessary treatment, not withholding necessary treatment.

16.17. The Decision Sequence

The combined findings of Technical Papers No. 2 and No. 3 suggest a more disciplined treatment sequence. The practitioner should first establish why the monument failed or became displaced. Foundation and bearing deficiencies should be corrected before strengthening the joint. The geometry should then be evaluated to determine how the monument carries its dead load and how it resists sliding and overturning without additional connection. If the assembly is inherently stable, a mineral-only or setting-based repair may be sufficient. If modest supplemental restraint is required, limited bonding should be considered. If substantial tensile, shear, bending, or overturning loads must cross the joint, more extensive adhesive bonding or mechanical reinforcement may be justified. If no treatment can provide adequate safety without unacceptable destruction of deteriorated historic material, alternative support or non-reassembly may need consideration. This sequence prevents the material from becoming the starting point. The monument determines the treatment.

16.18. A Revised Pinning-versus-Adhesive Framework

The following framework synthesizes the two papers:

Table 16.1: Pinning-versus-Adhesive Treatment Framework

Condition	Adhesive-only / limited bond	Pinning or mechanical reinforcement
Broad stable horizontal bearing	Often favorable	Usually unnecessary unless overturning demand requires it
Low, heavy monument component	Often favorable	Consider only with demonstrated need
Clean tablet fracture in sound marble	Potentially favorable	Consider when bending demand or geometry exceeds adhesive-only confidence
Thin or highly weathered tablet	Adhesive may be substrate-limited	Pinning may also be unsafe because insufficient sound stone exists
Tall narrow monument section	May be insufficient alone	Often merits serious consideration

Condition	Adhesive-only / limited bond	Pinning or mechanical reinforcement
Projecting element carrying sustained tension	Often questionable as sole restraint	Frequently appropriate
Existing reusable historic pin holes	Depends on geometry	Reuse may reduce new material loss
Severe sugaring around proposed drill zone	May favor broader surface restraint	Often contraindicated
Safety-critical falling hazard	Must demonstrate adequate capacity	Positive mechanical restraint may be preferred
Low consequence of joint release	Limited bonding or mineral setting attractive	Added reinforcement may be disproportionate

Note. This framework intentionally avoids automatic answers. The condition of the stone can move the decision in either direction.

16.19. Failure Hierarchy as the Final Arbiter

The central question can now be expressed more clearly than either “Should this be pinned?” or “Which adhesive should we use?” The practitioner should ask: **If this repair is subjected to a load greater than we intend it to experience, what is likely to happen next?**

Will a replaceable joint material crack?

Will a localized adhesive pad release?

Will a small area of marble detach?

Will a rigid dowel split the stone?

Will a fully bonded component remain attached while the base fractures?

Will a weak joint allow a heavy upper section to fall?

There may be no failure mode without consequence. The task is to choose the hierarchy that provides adequate ordinary stability while producing the least unacceptable extraordinary outcome. That is the connection between structural engineering and conservation ethics.

16.20. Implications for Gravestone Guardians Practice

The combined analysis supports several refinements to the current Gravestone Guardians approach. Akepox 5010 can remain a primary candidate for clean tablet fractures in marble

sufficiently sound to receive structural bonding, but its use should remain conditional upon fracture geometry and substrate assessment. Pratley Standard Setting Putty can remain a candidate for limited restraint in broad, compression-loaded multi-piece monuments, provided the monument is independently stable in bearing and the putty is not allowed to become a continuous structural bed. Lead wedges can continue to provide controlled spacing, bearing adjustment, and localized load distribution while being used in quantities and locations that avoid excessive point loading. Monument setting compound or compatible mineral joint material can maintain the perimeter without being expected to provide the principal structural bond. Pinning should be retained as an important structural option when geometry, loading, or safety requires positive reinforcement.

None of these materials should become the universal Gravestone Guardians solution. The most defensible organizational philosophy is not a favored product. It is a **treatment-selection hierarchy**.

16.21. The Middle Ground

The debate between traditional conservation and modern monument repair is sometimes framed as though practitioners must choose between two extremes. At one end is maximum reversibility: weak mineral materials, minimal adhesion, and avoidance of irreversible intervention. At the other is maximum structural permanence: full epoxy bonding, rigid pins, and connections intended never to move again. Historic cemetery monuments frequently require neither extreme. A more useful middle ground acknowledges that some permanence may be necessary while limiting where that permanence is introduced. It allows gravity and stone bearing to perform work they already perform effectively. It uses adhesive where adhesion is actually needed, pins where mechanical reinforcement is actually needed, mineral materials where mineral compatibility provides an advantage, and maintainable joints where future maintenance is inevitable.

That middle ground is not a compromise in the sense of accepting mediocre performance from competing philosophies. Properly developed, it is a distinct conservation strategy. Its governing principles are **adequate stability, minimum necessary intervention, functional separation, controlled bonded area, substrate-specific material selection, and deliberate failure hierarchy**. Those principles provide a more rigorous basis for historic marble monument repair than either universal pinning or universal avoidance of structural adhesives.

They also establish the foundation for the chapters that follow, where treatment selection can move from general principles to field assessment, decision matrices, formal

documentation of the Gravestone Guardians limited-bond model, and ultimately experimental validation.

17. Failure Modes of Adhesive Repairs

17.1. A Repair Should Be Evaluated by How It Fails

The immediate success of an adhesive repair is relatively easy to observe. The fragments fit together, the joint cures, the monument stands upright, and the repaired section does not move during ordinary handling. Long-term conservation success is more difficult to define because an apparently intact adhesive joint can coexist with developing damage elsewhere in the stone.

This distinction is central to the failure-hierarchy framework developed throughout this paper. A repair that remains bonded while marble fractures immediately beside it has performed successfully according to one narrow criterion—adhesive durability—while potentially performing poorly according to another—the preservation of original fabric. Conversely, an adhesive that releases under an unusually severe load may be described as having “failed” even though that release prevented a much larger loss of historic stone.

Failure should therefore not be treated as a binary condition in which the adhesive either holds or does not hold. The more useful questions are where the failure occurred, what initiated it, how much original material was lost, whether the monument remained safe, and how readily the resulting condition can be retreated.

The terminology used to describe adhesive failure is well established in materials testing. Conservation adds another layer by asking whether the location of failure represents an acceptable preservation outcome. Podany and colleagues demonstrated the importance of this distinction when marble specimens bonded with epoxy, polyester, and even concentrated Paraloid B-72 frequently failed cohesively within the marble rather than at the adhesive interface. The strongest joint is therefore not automatically the joint with the most favorable conservation failure (Podany et al., 2001).

A systematic failure taxonomy is necessary if different adhesive systems are to be compared meaningfully.

17.2. Adhesive Failure at the Stone Interface

Adhesive failure occurs when separation develops primarily along the boundary between the cured adhesive and the marble. The adhesive may remain substantially intact while detaching from one or both stone surfaces.

At first glance, this may appear to represent the ideal sacrificial outcome. If the adhesive releases cleanly and the marble remains intact, original material has been preserved. In some circumstances that is exactly the desired result.

The interpretation becomes more complicated when the failure occurs during ordinary service. An adhesive that routinely loses adhesion after seasonal cycling, moisture exposure, modest vibration, or normal monument movement does not provide adequate structural performance merely because the stone remains undamaged. Repeated treatment can itself produce cumulative damage through handling, cleaning, preparation, and renewed bonding.

Adhesive failure may result from several conditions: inadequate wetting of the marble surface, contamination, biological residue, moisture incompatible with the particular adhesive, insufficient surface preparation, incorrect resin-to-hardener ratio, incomplete cure, poor adhesion to a previous treatment, excessive stress at an edge, or environmental aging of the interface.

In weathered marble, apparent adhesive failure also requires careful examination. A thin layer of marble grains may remain attached to the resin, indicating that the bond did not actually fail at the chemical interface. Instead, the outermost stone layer failed cohesively. To the unaided eye, the adhesive may appear simply to have “popped off,” while microscopic examination would classify the event differently.

This distinction matters because the treatment response differs. True adhesive failure may suggest a problem with product selection or surface preparation. Cohesive loss of a friable surface indicates that the substrate itself was incapable of carrying the applied stress.

17.3. Cohesive Failure Within the Adhesive

Cohesive adhesive failure occurs when the bond remains attached to both marble surfaces but the cured polymer fractures through its own mass.

This can represent a favorable conservation hierarchy if the adhesive fails only after providing adequate service capacity and if the resulting pieces can be separated without significant stone loss. In such a case the modern repair material has become the sacrificial component.

The desirability of this failure mode should not be overstated. An adhesive deliberately selected to break within itself at very low loads could produce an unstable monument. Furthermore, fractured resin may remain strongly adhered to both stone surfaces, requiring mechanical or solvent-assisted removal before retreatment.

Bond-line thickness can influence cohesive failure. Thick adhesive masses contain larger volumes of polymer and may contain voids, incomplete mixing, filler discontinuities, or regions of differing cure. A thin, properly mixed structural epoxy may be much less likely to fail internally than a thick putty mass.

Cohesive adhesive failure is therefore most useful as a comparative laboratory observation rather than a universal treatment objective. A conservation-oriented system seeks acceptable overall failure consequences, not necessarily one predetermined microscopic fracture path.

17.4. Cohesive Marble Failure

Cohesive marble failure occurs when the adhesive and adhesive-stone interface remain sufficiently intact that fracture develops through the stone itself.

This is the failure mode most frequently cited in arguments against high-strength adhesives on historic marble. The concern is legitimate because the repair material is replaceable while original marble is not.

Yet cohesive marble failure requires interpretation within the loading context. If a repaired monument experiences an extreme impact sufficient to break sound marble elsewhere, the formation of a new fracture beside an intact adhesive joint does not demonstrate that the adhesive was necessarily inappropriate. The stone has finite capacity regardless of treatment.

The more concerning condition is cohesive failure under loads or environmental movements that the untreated monument should reasonably have accommodated. If a large rigid bonded area repeatedly transfers minor settlement or thermal displacement into adjacent weathered marble, the repair may be structurally overconstrained.

The location and quantity of stone loss therefore matter as much as the general failure category. A shallow loss of several grains beneath a small adhesive pad represents a very different conservation consequence from a deep conical breakout or a new fracture propagating across an entire monument component.

Future experimental work should record cohesive marble failure quantitatively rather than simply checking a box marked “stone broke.”

17.5. Surface Spalling

Surface spalling occurs when a relatively shallow layer of stone separates parallel or obliquely to the exposed surface. In adhesive repairs, this can develop when a strong bond engages only the outer portion of the marble and tensile or shear stresses cause that surface layer to detach from weaker material beneath it.

Weathered marble can be especially vulnerable because the adhesive may bond effectively to several millimeters of stone that remain internally weakened by

microcracking. The repaired surface then behaves as a relatively coherent composite layer attached to a less coherent substrate.

Spalling is significant because it can enlarge the visible footprint of a repair. An adhesive pad originally occupying a small concealed area may eventually detach with a larger plate of marble attached, converting a minimally visible intervention into a substantial surface loss.

This failure should be distinguished from simple adhesive detachment. Residual stone on the adhesive, the depth of the loss, and the character of the newly exposed surface provide evidence of the actual mechanism.

17.6. Edge Breakout

Edge breakout occurs when stresses associated with an adhesive, pin, wedge, or other restraint cause fracture to reach a nearby free edge.

Edges are mechanically vulnerable because less stone surrounds the loaded region. Weathering is also frequently more advanced at corners and edges because they experience greater exposure and can lose material from multiple directions.

Localized Pratley pads placed too close to the perimeter of a monument interface could theoretically produce edge breakout under overturning or peel loading. The same problem can occur around drilled dowels when insufficient stone remains between the hole and the nearest edge.

This failure mode has direct implications for treatment geometry. Structural restraint should generally be located within sufficiently substantial sound material rather than immediately behind a thin or sugared edge.

There is no universal minimum edge distance applicable to every adhesive pad because stone condition, pad size, component thickness, and loading vary. The general principle is nevertheless clear: **structural restraint requires enough surrounding historic material to distribute the force it introduces.**

17.7. Crack Migration

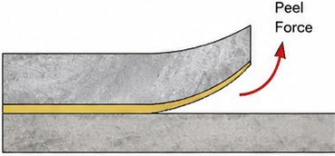
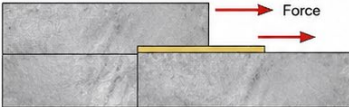
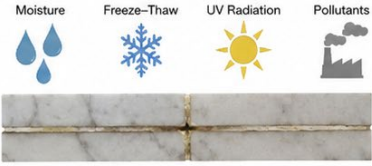
Crack migration occurs when a repaired fracture remains intact but subsequent movement creates a new fracture adjacent to or extending from the original repair. This is one of the most visually dramatic adhesive-related failure modes and one of the easiest to interpret too simplistically. A crack may migrate because the repaired section has become stronger or stiffer than surrounding marble. It may also follow a pre-existing microcrack or weak

grain boundary that would have governed failure regardless of the adhesive. In many cases both mechanisms contribute.

The distinction is especially important in tablet repairs. A transverse break repaired with structural epoxy may recover substantial continuity. During a later bending event, the old fracture no longer functions as the weakest plane, and the maximum tensile stress may initiate a new break nearby. From a strictly structural perspective, this may demonstrate successful restoration of continuity. From a conservation perspective, it also means that future damage now affects previously intact original material. The desirability of that outcome depends upon the magnitude of the initiating load and the alternatives available at the time of treatment. Crack migration should therefore be documented through photographs showing its relationship to the original joint rather than described merely as “epoxy caused another break.”

Because structural performance cannot be reduced to a simple holding-versus-failed distinction, Figure 17.1 compares several important adhesive-repair failure modes. The location of separation and the quantity of historic stone affected provide information that maximum failure load alone cannot supply.

Figure 17.1: Common Failure Modes of Adhesive Repair

1. Adhesive (Cohesive) Failure  Failure occurs within the adhesive leaving adhesive on both surfaces.	2. Adhesive-to-Stone (Interfacial) Failure at One Surface  Adhesive separates from one substrate leaving little or no adhesive on that surface.	3. Adhesive-to-Stone (Interfacial) Failure at Both Surfaces  Adhesive separates cleanly from both substrates.
4. Substrate (Material) Failure Adjacent to the Bond  Fracture occurs in the stone close to the bond due to high stress concentration.	5. Cohesive Tear in Substrate  Crack propagates through the stone material away from the adhesive.	6. Mixed-Mode Failure  Failure involves a combination of adhesive and substrate failure.
7. Peel (Tensile) Failure  Tensile or peel forces exceed adhesive strength, causing separation starting at an edge.	8. Shear (Sliding) Failure  Shear stresses exceed adhesive strength, causing the bonded parts to slide.	9. Environmental Degradation  Environmental factors degrade the adhesive or interface, reducing bond strength over time.

Note. Actual failures are often a combination of the modes shown. Proper material selection, surface preparation, and design to minimize stress concentrations help prevent these failures.

17.8. Secondary Fracture Remote from the Repair

Not all treatment-related fractures develop immediately beside the adhesive. A highly rigidly coupled monument can transfer movement through an entire component and produce failure at a weaker location some distance away. A fully bonded die-to-base interface, for example, might remain intact while settlement induces cracking at the base, at another joint, or within a projecting architectural feature. Such remote failures illustrate why monument repair must be understood as a structural system rather than a collection of independent joints. The relationship between treatment and remote fracture may be difficult to establish conclusively. Foundation movement, previous cracks, environmental deterioration, and impact can all contribute. Nevertheless, a major change in stiffness at one interface can alter load distribution throughout the monument. Post-treatment monitoring should therefore examine the entire assembly, not only the repaired joint.

17.9. Debonding from Environmental Aging

A joint that performs well immediately after treatment can gradually lose adhesion through environmental exposure. Moisture, thermal cycling, ultraviolet radiation where adhesive is exposed, repeated freeze-thaw conditions, chemical contaminants, and polymer aging can change either the resin or the stone surrounding it. NPS guidance identifies salt crystallization and freeze-thaw cycling as important deterioration mechanisms in grave markers because moisture can enter cracks and pores and contribute to progressive stone damage. An adhesive does not exist independently of these processes. Even if the polymer itself remains chemically stable, the marble immediately beneath it may continue to deteriorate (National Park Service, n.d.-b). Environmental debonding may therefore occur through progressive weakening of the substrate rather than degradation of the adhesive. This is an important distinction for product evaluation. A twenty-year-old epoxy that remains hard and intact while detaching with a thin layer of deteriorated marble has not necessarily experienced polymer failure. The repaired system has failed because the substrate continued to change around a comparatively stable material.

17.10. Thermal-Cycling Failure

Marble and polymer adhesives respond differently to temperature change. Calcite is itself anisotropic, while organic polymers generally possess substantially different thermal-expansion and temperature-dependent stiffness behavior. Repeated heating and cooling can therefore subject an adhesive-stone interface to cyclic strain even where no external structural load changes. The effect is likely to be most important where large bonded areas constrain movement. A narrow fracture bond contains little polymer and short movement distances. A full horizontal adhesive layer spanning a large monument interface can accumulate substantially greater differential dimensional change across its width. Thermal-cycling failure can appear as edge debonding, microcracking, gradual opening of the interface, cohesive stone loss, or progressive extension of nearby fractures. Laboratory environmental testing should therefore include repeated thermal exposure before mechanical evaluation rather than treating room-temperature initial strength as the principal measure of performance.

17.11. Creep and Time-Dependent Movement

Creep is time-dependent deformation under sustained load. It is particularly relevant to thermoplastics, elastomers, lead, and some polymer systems, but no material should be assumed perfectly immune to time-dependent behavior. An adhesive pad carrying persistent shear or tensile load may gradually deform even though the applied force is far below its short-duration failure strength. The effect generally increases with temperature.

This is one reason the Gravestone Guardians limited-bond model places particular emphasis on independent bearing. If the monument's dead load is carried through stone and appropriate bearing materials, the adhesive does not remain continuously loaded in tension merely to keep the component in position. A repair that depends upon a polymer permanently resisting a high sustained peel or shear load should be evaluated differently from one in which the same polymer acts primarily during occasional lateral disturbance. The duration of loading is therefore as important as its magnitude.

17.12. Moisture-Related Failure

Moisture can affect adhesive repairs through several pathways. It can interfere with initial adhesion in products not designed for damp substrates, transport salts beneath or beside a repaired interface, contribute to deterioration of the marble substrate, alter the properties of some polymers, and create freeze-related stresses in cracks and pores. A relatively impermeable repair can also alter local drying. Moisture entering the stone from another direction may move toward the edges of the adhesive zone rather than passing through it. This does not justify the generalized claim that epoxy “traps moisture” and therefore should never be used. The extent of the bonded area, joint orientation, stone porosity, adhesive permeability, and exposure all matter. A narrow epoxy fracture line and a full-surface epoxy bedding layer should not be assumed to have equivalent hydric effects. Failure analysis should therefore record staining, dampness, efflorescence, salt crusting, biological growth, or freeze-related damage near the repair rather than examining mechanical separation alone.

17.13. UV Degradation and Discoloration

Structural adhesives concealed within a joint receive relatively little direct ultraviolet exposure. Resin visible at exterior fracture lines or perimeter joints is more vulnerable. UV degradation can produce yellowing, chalking, embrittlement, loss of gloss, or changes in mechanical properties depending upon formulation. Discoloration is not merely cosmetic. A conspicuous yellow repair against white marble can encourage premature mechanical removal or replacement of an otherwise stable joint. The visual aging of a material therefore influences the likelihood of future intervention. This issue is particularly relevant to materials such as Domo 10, whose current technical data identify substantial yellowing under the manufacturer's simulated outdoor exposure, and less concerning for formulations specifically designed to limit discoloration. The practical conservation lesson is to minimize unnecessary exposed polymer regardless of product.

17.14. Staining

Staining may arise from the adhesive itself, from pigments or fillers, from oils or plasticizers in setting compounds, from corrosion products associated with reinforcement, or from moisture and dirt accumulating preferentially around a repair. Low-viscosity resins can produce dark halos where liquid components penetrate porous stone beyond the visible joint. The effect can remain even if the structural bond performs perfectly. Staining can also be secondary. A hard repair surface may shed water differently from surrounding marble and create persistent wetting patterns at the interface. Biological growth may then concentrate around the repair. Documentation should distinguish staining that appears immediately during treatment from discoloration developing gradually over years. Their causes are likely to differ.

17.15. Brittle Fracture of the Repair Material

Rigid epoxies, polyester mastics, mineral grouts, and hard mortars can themselves fracture when deformation exceeds their capacity. Such fracture may initially appear favorable because the treatment material fails rather than the marble. The broken repair can nevertheless remain wedged tightly within the joint and continue transferring stress. Mineral grouts can develop fine internal cracking without complete separation. Epoxy putties may fracture locally while remaining attached over large areas. Mortar can crack through its center while both edges remain strongly bonded to marble. The conservation outcome therefore depends upon whether material failure actually releases stress from the historic stone. A cracked repair is not necessarily a sacrificial repair if it remains mechanically locked into the surrounding substrate.

17.16. Failure of Bearing Rather Than Bonding

An intact adhesive can coexist with failing bearing. Lead wedges may deform, shims may move, mortar beds may shrink, stone asperities may crush, or foundation settlement may change contact patterns. The adhesive then begins carrying loads it was not intended to carry. A limited-bond system is particularly dependent upon recognizing this sequence. The adhesive may have been designed only to resist lateral movement, but loss of bearing can gradually place it into sustained tension or bending. Changes in joint width, rocking, newly exposed shims, tilting, or edge crushing may therefore represent early warning signs even while the adhesive pads remain hidden and intact. Monitoring should focus upon load-path changes, not merely the visible bond line.

17.17. Failure of the Perimeter Joint

Perimeter compound or lime mortar will often deteriorate sooner than concealed structural restraint. This should not automatically be considered a failure of the complete monument repair. A maintainable perimeter layer is expected to require renewal. Cracking, shrinkage, localized separation, or loss of setting compound may indicate normal aging rather than structural instability. The critical question is whether the underlying monument remains securely supported and restrained. This distinction should be incorporated into public education and maintenance planning. Replacing deteriorated setting compound periodically is preferable to designing every material in the assembly to be permanently immovable.

17.18. Pin-Related Failure

Although the present paper concentrates upon adhesives, failure taxonomy must include mechanical reinforcement because pinned and bonded systems often compete for the same treatment decision. Pin-related failures include stone breakout around the drilled hole, splitting from inadequate edge distance, cracks initiated at the end of the dowel, corrosion expansion in noncorrosion-resistant metals, loosening of the anchoring adhesive, or bending and fracture of the reinforcement itself. NPS documentation from St. Paul's Church illustrates the historic problem of iron pins rusting and contributing to stone cracking or displacement; later repairs replaced deteriorated iron with stainless steel (National Park Service, n.d.-f). These failures reinforce the central argument of Technical Paper No. 2: mechanical reinforcement does not eliminate failure. It changes the location and mechanism through which failure occurs.

17.19. Classifying Failure Severity

For research and field monitoring, failure should be classified by consequence rather than by adhesive condition alone.

A useful preliminary system could include four levels.

Level 1 — Treatment-material deterioration without original stone loss. Examples include cracked perimeter compound, minor adhesive discoloration, or cohesive failure confined to replaceable repair material.

Level 2 — Localized interface failure with negligible or superficial stone loss. Examples include adhesive release carrying only loose grains or small edge losses that do not affect structural integrity or significant historic detail.

Level 3 — Significant cohesive marble damage. Examples include measurable spalling, deep breakout, new secondary cracking, or loss affecting inscription or carved detail.

Level 4 — Structural or catastrophic failure. Examples include collapse, substantial fragmentation, overturning, or a repair failure creating a safety hazard.

Such classification does not replace mechanical measurements. It provides a conservation scale against which those measurements can be interpreted.

A system carrying the highest ultimate load may still receive a poorer conservation rating if its eventual failure consistently produces Level 3 or Level 4 damage.

17.20. Failure as Evidence

Every failed historic repair contains information. The location of residue, fracture shape, corrosion, staining, joint width, surviving shims, old drill holes, and remaining setting materials can reveal how the monument was previously assembled and why that assembly stopped performing. Removing these materials without documentation discards evidence that could improve the next treatment. NPS cemetery guidance emphasizes documenting monument condition and repair history before and during work, including identification of material, damage, fragments, and treatments used (National Park Service, n.d.-c). Failure analysis should therefore become part of the treatment process rather than merely an explanation developed after something goes wrong. The practitioner should ask not only how to make the new repair stronger, but what the old failure reveals about the forces acting on the monument.

18. Assessing the Stone Before Selecting an Adhesive

18.1. Treatment Selection Begins with Examination

The conservation suitability of an adhesive cannot be determined until the monument itself has been examined. This proposition may appear self-evident, yet product-based repair discussions frequently reverse the sequence. A broken marble tablet is assumed to require epoxy or pins; a loose die is assumed to require Pratley or dowels; an open crack is assumed to require grout. The material is selected before the failure mechanism and substrate have been defined.

Professional conservation guidance places examination first. The American Institute for Conservation requires thorough examination and documentation before intervention and directs practitioners to select treatment materials according to the objectives and potential future effects of the specific treatment. NPS cemetery guidance similarly treats condition assessment as the basis for identifying hazards, prioritizing work, and determining appropriate stabilization and conservation measures (American Institute for Conservation, n.d.; National Park Service, n.d.-c). The field assessment proposed here is therefore not merely a quality-control step for adhesive application. It is the process that determines whether structural adhesive should be used at all.

18.2. Identify the Monument Configuration

The first stage is to determine what type of monument is being evaluated and how it was intended to remain stable. A ground-supported tablet, slotted tablet, die-and-base monument, multi-tier pedestal, obelisk, column, urn, ledger, sculptural memorial, and architectural tomb respond differently to load. The assessment should record component dimensions, approximate thickness, number of pieces, joint orientations, visible pins or cramps, socket geometry, base dimensions, embedment, and apparent original setting method. The practitioner should then identify which portions of the monument rely principally upon gravity, which rely on ground embedment, and which require positive mechanical connection. This prevents treatment of fundamentally different monuments as though each were simply “broken marble.”

18.3. Establish the Cause of Failure or Displacement

Repair should address the mechanism that produced instability rather than merely closing its visible symptom. Questions include whether the stone fractured from impact, ground movement, foundation settlement, frost heave, corrosion of embedded metal, vandalism, tree damage, mower contact, previous inappropriate repair, structural overload, or gradual material deterioration. A monument that separated because old setting compound failed

after a century may require a very different intervention from one repeatedly displaced by foundation movement. NPS cemetery guidance emphasizes assessing both the monument and its surrounding environment, including standing water, landscape conditions, structural defects, and sources of continued deterioration (Gale et al., 2016). If the cause remains active, strengthening the joint can simply redirect the next failure elsewhere.

18.4. Determine Whether the Monument Is Currently Safe to Handle

Before detailed adhesive assessment begins, immediate instability must be addressed. Loose elevated sections, severely leaning monuments, fractured tablets held only by small remaining areas, or unsupported projecting components can present hazards to both the stone and the practitioner. Temporary stabilization may be required before examination. NPS post-disaster cemetery guidance documents the use of temporary supports and emphasizes identifying unsafe conditions before repair work proceeds (Church, 2021). A structurally hazardous monument should not be manipulated simply to perform a dry fit or test an adhesive theory. Where component size, height, or instability exceeds the capabilities of the preservation team, rigging, engineering, or specialist monument-setting support should be obtained.

18.5. Identify the Stone

The substrate should be identified as accurately as practical. The present paper focuses upon marble, but cemetery monuments can contain limestone, granite, slate, sandstone, concrete, cast stone, zinc, metal, and combinations of materials. Even within marble, significant differences exist among fine-grained calcitic marble, coarse-grained varieties, dolomitic marble, and stones historically marketed as “marble” despite different geology. Stone identification helps predict likely weathering mechanisms and informs interpretation of cracks and surface loss. A product performing well on dense granite should not be assumed to behave identically on weathered calcitic marble. Where identification is uncertain and the treatment is structurally consequential, further expertise may be warranted.

18.6. Assess Surface Cohesion

Surface cohesion is one of the most important factors in determining whether marble can receive an adhesive. The practitioner should look for granular disintegration, sugaring, flaking, exfoliation, scaling, powdering, or grains that detach under extremely gentle examination. NPS cleaning guidance specifically identifies sugaring and related deterioration as conditions requiring caution because fragile stone surfaces can be damaged even by relatively gentle maintenance. The same observation has greater structural importance in adhesive repair: a surface too weak to tolerate gentle

manipulation may not be suitable for concentrated adhesive loading (National Park Service, n.d.-b). Assessment should focus particularly on the actual intended bonding region rather than the exterior surface alone. A tablet may show moderate weathering externally while exposing relatively sound crystalline marble along a recent fracture. An old break exposed for decades may be deteriorated deeply into the fracture zone. The decision should follow the material that will carry load.

18.7. Examine the Fracture Surface

Where pieces are already separated and can be examined safely, the fracture itself provides substantial information. The practitioner should determine whether the break is clean or weathered, whether fragments interlock, whether significant material is missing, whether the surfaces contain previous resin or mortar, and whether cracks extend beyond the visible fracture. Bright crystalline surfaces may suggest a relatively recent or protected break. Rounded, dirty, biologically colonized, or granular surfaces suggest prolonged exposure. The fracture should also be examined for signs that it originated from a prior repair or structural defect. Drill holes, embedded metal, rust staining, previous adhesive, saw cuts, and parallel cracks can alter the next treatment. No structural adhesive should be applied until old material that would interfere with the new load path has been evaluated.

18.8. Evaluate Grain Cohesion Beyond the Immediate Break

A sound-looking fracture surface can be misleading if the stone immediately behind it contains a network of microcracks. Visible side cracks, edge separations, hollow-sounding regions, previous spalls, and subtle parallel fractures may indicate that adhesive would bond a fragment to marble that is itself only partially attached to the monument. This is particularly important with localized putty pads. The pad may adhere perfectly to a broad surface while the loaded zone separates several millimeters deeper into the stone. Where uncertainty is significant, the treatment should become more conservative. The objective is not to prove the stone strong enough to justify a preferred adhesive but to identify whether the substrate can safely carry the proposed load.

18.9. Assess Moisture Conditions

The monument should be examined for active moisture sources and persistent dampness. Relevant observations include poor drainage, standing water, soil contact, open horizontal joints, capillary moisture from foundations, nearby irrigation, shaded conditions, biological growth patterns, and water entering from higher components. NPS cemetery resources repeatedly identify moisture, drainage, and freeze-thaw as important contributors to grave-marker deterioration (National Park Service, n.d.-b). The presence of moisture does not

automatically exclude every epoxy or mineral grout. Several adhesives are specifically formulated for slightly damp stone. The important question is whether moisture represents a continuing deterioration mechanism that must be corrected before bonding. An adhesive tolerant of damp marble is not a solution to chronic water entry.

18.10. Look for Salts

Efflorescence, powdery deposits, crusts, unusual discoloration, or repeated damp-dry patterns may indicate soluble salts. NPS guidance recognizes salt crystallization as capable of producing pressures within pores sufficient to contribute to disintegration of stone surfaces (National Park Service, n.d.-b). A salt-contaminated fracture presents two problems. Deposits can interfere with immediate adhesion, and continuing crystallization can weaken the stone beneath an otherwise durable repair. The treatment should therefore address active salt sources rather than simply cleaning the visible joint and bonding across it. Where salt activity is substantial and unresolved, postponing structural adhesive work may be more appropriate than creating a permanent joint in a changing substrate.

18.11. Assess Previous Repairs

Previous treatment should be mapped before new material is selected. The assessment should identify visible epoxy, polyester, silicone, caulk, cement, mortar, lead, iron, stainless steel, copper alloys, fiberglass, grout, repair mortar, consolidant, or other materials where possible. Old drill holes deserve particular attention. Their presence can weaken the section, constrain future pin placement, or provide an opportunity to reuse an existing intervention rather than drilling additional original marble. Previous silicone contamination may compromise adhesion. Rust staining can indicate concealed ferrous reinforcement. Hard cement patches may hide cracks or transfer stresses into adjacent stone. NPS documentation guidance specifically recommends gathering records and historical information about prior repairs before treatment (National Park Service, n.d.-c). The previous repair is part of the present monument condition whether or not it would be selected today.

18.12. Evaluate Bearing Surfaces

For multi-piece monuments, the bearing assessment is at least as important as the adhesive assessment. The components should be dry-fitted where safe and practical. The setter should determine where the surfaces contact naturally, whether the upper component rocks, whether remnants of old mortar or compound create high points, whether old lead remains, and whether material loss prevents stable support. The goal is to answer a crucial question: **Can the monument remain stable under its own weight before structural adhesive is added?** If the answer is no, the bearing problem must be

corrected first. Pratley Putty should not be used simply to fill every void until the upper stone stops rocking. Likewise, a full epoxy bed should not substitute for diagnosis of why broad bearing has been lost.

18.13. Assess Foundation and Lower Components

An adhesive repair at the upper joint cannot compensate for a moving foundation. The assessment should include level, settlement, erosion, soil loss, tilting, exposed foundation edges, frost movement, root activity, sinking, and deterioration of lower monument components. NPS resetting guidance demonstrates that ground movement, drainage, frost, biological activity, and other environmental factors can continue shifting even relatively simple upright headstones. Large multi-piece monuments are subject to the same environment even if their foundations differ (National Park Service, n.d.-e). If significant active movement is evident, the foundation should be stabilized before rigidly reconnecting upper components. Otherwise, the repair may simply convert visible joint movement into stone fracture.

18.14. Determine the Expected Load at the Joint

The practitioner should identify qualitatively what the repaired connection must resist. For a tablet fracture, bending and tension may dominate. For a heavy horizontal die, compression and friction may already carry most ordinary loads, leaving the repair to resist modest shear or uplift. For a tall narrow component, overturning may control. For a projecting element, sustained tension or bending may require positive mechanical reinforcement. This load classification does not require full engineering analysis for every simple marker. It does require enough mechanical understanding to prevent selection of materials based solely on product familiarity. Where the forces or consequences exceed reasonable field judgment, formal structural evaluation should be sought.

18.15. Consider the Consequence of Joint Release

The required strength of a repair depends partly on what happens if the joint releases. If a low die shifts slightly on a broad base, the result may be visible displacement requiring resetting. If an elevated urn or sculptural fragment releases, it may fall, shatter, injure a visitor, or damage surrounding monuments. This difference may justify substantially greater intervention in the second case. Failure consequence should therefore be recorded during assessment rather than assumed to follow directly from stone size. A comparatively small fragment can create a high hazard if elevated; a massive low component may present far lower release consequence because it cannot travel far.

18.16. Determine Whether Reversibility Is Operationally Important

Every treatment should preserve future options where practical, but the value of retreatability varies among interventions. A museum-quality sculptural fragment expected to undergo future analytical examination may warrant a particularly strong preference for solvent-responsive systems. A large cemetery die whose future dismantling would require a crane regardless of adhesive chemistry may derive more practical benefit from localized accessible bonding than from theoretical full chemical reversibility. This does not reduce conservation ethics to convenience. It recognizes Appelbaum's distinction between abstract reversibility and real-world retreatability: treatments exist in degrees, and even irreversible treatments should be evaluated according to whether future intervention remains possible. The assessment should therefore ask how the monument would actually be retreated rather than merely whether the resin appears on a list of soluble materials.

18.17. Evaluate Visibility and Aesthetic Sensitivity

Some joints are concealed; others pass directly through inscriptions, polished surfaces, carved motifs, or faces. The tolerance for resin squeeze-out, discoloration, staining, or visible bond lines changes accordingly. A highly visible fracture on white marble may favor a low-yellowing adhesive and particularly controlled application. A concealed horizontal pad can prioritize mechanical behavior over optical clarity. Aesthetic compatibility is not secondary to conservation. Poorly aging visible repairs can lead to unnecessary future intervention and permanently alter the monument's appearance. Treatment selection should therefore consider whether the adhesive remains visible after completion and how its appearance is likely to change.

18.18. Determine Environmental Exposure

The assessment should record sun exposure, shade, prevailing moisture, freeze-thaw conditions, vegetation, irrigation, tree cover, road salts, flooding, and other environmental factors relevant to long-term performance. Two identical adhesives used on identical marble can age differently when one joint remains sheltered beneath a broad cap and the other is fully exposed to direct solar heating and rain. This is particularly important when considering materials with comparatively low glass-transition temperatures, limited UV stability, or sensitivity to persistent moisture. Exterior rating by a manufacturer is useful evidence but cannot substitute for understanding the actual exposure condition.

18.19. Decide Whether Adhesive Is Necessary

After the preceding information has been gathered, the practitioner should ask a question that is often skipped: **Does this monument require structural adhesive at all?** A stable

multi-piece monument may need resetting, bearing correction, and an appropriate perimeter joint without additional structural bonding. A historically mortared interface may be adequately restored using compatible mineral material. A low component with little overturning risk may remain stable through mass and friction. Conversely, a fractured tablet plainly requires some method of restoring structural continuity if it is to be returned to service. The absence of adhesive should therefore remain a legitimate treatment option rather than a failure to make a decision. AIC guidance explicitly recognizes nonintervention as appropriate where treatment would not best serve preservation (American Institute for Conservation, n.d.).

18.20. Determine Whether the Monument Should Be Reassembled

An even more fundamental question follows. Some fragments may be too deteriorated to return safely to their original position. A severely sugared elevated component may not contain sufficient sound material for adhesive or pins. Reassembling it could create both preservation and safety hazards. In those cases, stabilization in a different configuration, protective storage, reproduction, external support, or non-reassembly may be more responsible than escalating intervention until the original geometry can be recreated. Minimum intervention does not require restoration of every monument to an imagined pristine configuration. Preservation sometimes means accepting evidence of damage while preventing additional loss.

18.21. Proposed Field Assessment Categories

For practical Gravestone Guardians use, the examination can eventually be organized around six assessment categories without reducing professional judgment to a checklist:

Table 18.1: Proposed Field Assessment Categories for Structural Repair

Assessment Area	Principal Question
Stone	Is the marble sound enough at the proposed load-transfer zone to accept the treatment?
Geometry	How is the monument supposed to carry weight and resist movement?
Failure Cause	Why did the monument break, separate, or move?
Environment	Are moisture, salts, settlement, frost, or other active deterioration processes unresolved?
Structural Demand	What loads must the repaired joint actually resist, and what happens if it releases?

Assessment Area	Principal Question
Future Treatment	How much historic material will be permanently altered, and how could the repair be retreated?

Note. This framework is intentionally diagnostic rather than product specific. Only after these six questions are addressed should adhesive selection begin.

19. Adhesive Selection Framework

19.1. From Product Preference to Treatment Selection

An adhesive-selection framework should not function as a chart that identifies one preferred product for every type of broken monument. Such a chart would reproduce the very problem this paper has attempted to correct. The appropriate sequence begins with the monument condition, identifies the structural function that must be restored, eliminates materials incompatible with the substrate or environment, and only then compares viable products. The framework developed here therefore operates through progressive decisions rather than a simple ranking. Its intended outcome may be Akepox 5010, Pratley Standard Setting Putty, a thermoplastic acrylic, an intervention-layer system, mineral grout, lime mortar, mechanical reinforcement, a combined system, no adhesive, or no immediate reassembly. The material is the result of the reasoning process rather than its starting point.

19.2. Decision 1 — Is the Stone Sound Enough to Receive Structural Load?

The first threshold is substrate integrity. If the proposed bonding or pinning zone is severely granular, deeply sugared, actively delaminating, extensively cracked, or otherwise unable to carry structural stress, adhesive selection should stop. Increasing adhesive strength cannot correct the absence of sound substrate. The repair concept must instead change through broader support, stabilization, consolidation where independently justified, mechanical support outside the weak zone, reduction of load, or non-reassembly. If the substrate is sound or sufficiently coherent within the intended load path, treatment selection can proceed. This first threshold prevents the practitioner from attempting to solve a stone problem by purchasing a stronger adhesive.

19.3. Decision 2 — Is the Failure Mechanism Understood?

If the monument continues to move because of settlement, drainage problems, corrosion, foundation rotation, or another active mechanism, that cause should be addressed before permanent structural bonding. NPS condition-assessment guidance places substantial emphasis on documenting the environment and structural condition precisely because successful preservation depends upon correcting or accommodating the cause of deterioration rather than treating only its visible symptom. A joint should not be strengthened until the practitioner understands what caused it to open. If the failure was a discrete event—such as impact—and the underlying system remains stable, structural repair may proceed more directly.

19.4. Decision 3 — Is Structural Bonding Required?

The next question distinguishes between a support problem and a bonding problem. If the component is stable through gravity, bearing, socketing, or historically appropriate mortar, structural adhesive may not be necessary. If a clean fracture must transmit bending or tension, adhesive is likely required. If a broad horizontal joint requires only modest resistance to sliding or accidental disturbance, limited adhesive restraint may be appropriate. If substantial uplift, overturning, or sustained tensile load exists, full bonding or mechanical reinforcement may need consideration. This decision determines the **role** of adhesive before a product is selected.

19.5. Decision 4 — What Type of Joint Exists?

Joint geometry narrows the material options significantly. A close-fitting fracture favors thin structural adhesive. A wider irregular break may require separate adhesive and loss-compensation materials. A large horizontal bearing interface favors support and localized restraint rather than automatic full bonding. An internal inaccessible void favors injectable grout. An exposed perimeter joint favors maintainable setting or pointing material. A drilled anchorage requires an appropriate pin-setting adhesive or grout. The same material should not be selected merely because it can physically be forced into all of these conditions.

19.6. Decision 5 — What Level of Restraint Is Required?

Three broad restraint categories are useful.

Low restraint demand

The monument is inherently stable through gravity, geometry, or embedment. The treatment principally restores alignment, closes a joint, or resists incidental movement.

Mineral setting materials, traditional perimeter compounds, or no structural adhesive may be sufficient.

Moderate restraint demand

The monument is independently supported but requires supplemental resistance to sliding, rocking, or separation.

Localized adhesive systems such as the Pratley limited-bond approach become appropriate candidates.

High restraint demand

The joint must transmit substantial bending, sustained tension, major shear, overturning forces, or prevent a potentially dangerous elevated component from releasing.

Continuous structural adhesive, mechanical reinforcement, or a combined engineered system may be required.

These categories do not correspond to exact load values because monument geometry varies. They create a rational sequence for deciding whether increasingly invasive intervention is warranted.

19.7. Decision 6 — How Important Is Retreatability?

Retreatability should then influence selection among materials capable of carrying the required load. Where structural demand is modest and future disassembly is particularly important, thermoplastic adhesives or mineral systems may offer meaningful advantages. Where higher structural capacity is required, intervention layers may allow strong thermosetting adhesives to be used while preserving a chemically weakenable interface. Where direct permanent epoxy provides the simplest reliable solution, its bonded area should be minimized and documented. Where pins are required, existing holes should be considered before new holes are drilled, provided they remain mechanically appropriate. The objective is to preserve future options proportionately rather than pursuing reversibility at the expense of necessary stability.

19.8. Decision 7 — What Environment Will the Joint Experience?

Exterior exposure can eliminate otherwise attractive adhesive options. Products intended principally for interior use should generally not be selected for exposed cemetery marble without specific evidence supporting such use. Polyester mastics with poor UV or freeze-temperature recommendations become less attractive. Thermoplastic acrylics require particular caution where sustained load and high solar temperatures could approach their softened mechanical region. Exterior-rated structural epoxies become more compelling where weather resistance is necessary. Mineral mortars and grouts may provide better hydric compatibility in broad treatments but still require freeze-thaw and curing considerations. Environment should therefore function as a screening factor rather than an afterthought.

19.9. Decision 8 — What Failure Consequence Is Acceptable?

Once several materials can satisfy the normal service requirement, their probable failure modes should be compared. A system should be preferred where future overload is expected to produce limited repair-material failure or localized, manageable stone loss rather than catastrophic fragmentation. This criterion may favor limited bonding over full-

area epoxy in a low monument. It may favor mechanical reinforcement over a sacrificial adhesive in an elevated component where release would cause a fall. There is no universal preferred failure mode. The correct hierarchy depends upon both preservation consequence and safety consequence.

19.10. Preliminary Material Suitability Matrix

The following matrix summarizes the roles developed throughout this paper.

Table 19.1: Preliminary Material Suitability Matrix by Repair Function

Material/System	Close Tablet Fracture	Multi-Piece Restraint	Internal Void/Delamination	Bedding	Perimeter Joint	Relative Retreatability
AKEPOX 5010	Preferred candidate when marble is sound	Acceptable selectively; full-area use requires justification	Limited specialized use	Generally avoid as primary bedding	Generally avoid	Low
Pratley Standard Setting Putty	Generally not preferred for thin clean breaks	Preferred candidate for localized restraint	Specialized	Avoid as primary continuous bedding	Avoid	Low chemically; potentially moderate geometrically
Tenax Domo 10	Structurally capable; generally not preferred over 5010 without specific reason	Structurally capable; potentially excessive	Limited	Generally avoid	Avoid	Low
HXTAL NYL-1	Specialized candidate	Limited	Specialized	Avoid	Avoid	Low
Paraloid B-72/B-48N systems	Experimental/specialized	Limited where loads are modest	Potentially useful	Avoid for substantial sustained bearing	Specialized	High relative to thermosets
B-72 intervention layer + epoxy	High-priority experimental candidate	Experimental	Specialized	Not primary bedding	Not primary joint material	Potentially moderate-high
IG10 or similar mineral grout	Specialized; not default for close break	Limited	Preferred candidate where geometry suits injection	Possible specialized role	Generally not pointing material	Moderate to low depending upon depth
NHL/lime mortar	Not primary structural fracture adhesive	Appropriate where inherent stability is sufficient	Appropriate formulated grouts for voids	Preferred candidate in compatible mineral bedding applications	Preferred candidate where historically/materially appropriate	Generally favorable
Monument setting compound	No	Secondary restraint only	No	Secondary interface role	Preferred candidate in appropriate flat-base joints	Favorable relative to structural resin
Pins/dowels + adhesive	Conditional on structural need and stone thickness	Preferred where positive mechanical restraint is necessary	No	No	No	Low; highly geometry-dependent

Note. The matrix deliberately distinguishes preferred candidate from universally approved material. Every entry remains conditional upon stone condition, workmanship, and structural demand.

19.11. Four Treatment Categories

For field communication, individual material decisions can also be grouped into four broader categories.

Preferred

A material or system is **Preferred** when its properties and geometry closely match the required function and no less invasive adequate treatment is apparent.

AKEPOX 5010 on a sound close-fitting tablet fracture and localized Pratley restraint within a stable multi-piece assembly may fall into this category under the conditions defined in this paper.

Acceptable With Limitations

A material is **Acceptable With Limitations** when it can perform the required role but introduces concerns requiring specific mitigation.

Examples could include thermoplastic acrylics in exterior structural applications, full-area epoxy on sound marble where broad structural coupling is genuinely required, or certain mineral grouts in wider structural cracks.

Specialized Application

A **Specialized Application** requires unusual geometry, additional expertise, testing, or engineering justification.

Examples include intervention layers, HXTAL or Epo-Tek in exterior monument repair, composite reinforcement, elastomeric bearing systems, or unusual grout configurations.

Generally Avoid

A system is **Generally Avoided** when another available treatment ordinarily offers a better balance of durability, compatibility, retreatability, or workmanship.

Examples include conventional interior-rated polyester mastic for exposed historic marble, structural epoxy used solely as perimeter pointing, silicone-based consumer sealants without stone-specific justification, or continuous epoxy bedding where stable bearing can be achieved without it.

“Generally avoid” is not equivalent to “never use.” It identifies a high burden of justification.

19.12. Tablet-Fracture Decision Path

For a broken marble tablet, the selection process can be summarized conceptually. If the marble around the break is structurally inadequate, do not proceed directly to structural bonding. If the marble is sound enough, determine whether the fragments fit closely and whether significant material is missing. A clean, tight fracture creates a strong case for minimum-volume structural adhesive. AKEPOX 5010 currently represents the leading GG candidate. If the fracture is wider, highly irregular, or partially missing, adhesive and loss compensation should be separated where practical. If ordinary loads are expected to create unusually high bending demand, evaluate whether adhesive alone is adequate. If mechanical reinforcement is needed, ensure sufficient sound stone exists for drilling and that the pinning failure mode is preferable to adhesive-only repair. If neither approach provides adequate capacity without disproportionate damage, alternative support or non-reassembly should be considered. The decision does not begin with “epoxy or pin.” It begins with whether the tablet can safely function again.

19.13. Multi-Piece Monument Decision Path

A multi-piece monument follows a different sequence. First, determine whether the foundation and lower component are stable. Second, dry-fit and establish whether broad bearing can be restored. Third, determine whether gravity and friction alone provide sufficient ordinary stability. If they do, structural adhesive may be unnecessary. If modest supplemental restraint is desirable, limited-bond reassembly becomes the principal candidate. If substantial overturning or elevated release risk exists, mechanical reinforcement or a more extensive engineered bond should be evaluated. The perimeter material should then be selected separately according to exposure, historical evidence, and maintainability. This sequence prevents the common mistake of using adhesive to correct problems that properly belong to the foundation, bearing, or joint-maintenance system.

19.14. Internal Crack and Void Decision Path

Where the problem is an internal void, delamination, or inaccessible separation rather than complete component fracture, injection becomes more relevant. The practitioner should determine whether the void is connected and injectable, whether the receiving material is sound enough to withstand injection pressure, and whether mineral or polymer grout best matches the substrate and structural demand. IG10 or lime-based hydraulic grout may be appropriate where distributed mineral reconnection is required. Structural epoxy injection may be justified where high tensile capacity is necessary and mineral grout would be inadequate. The choice should remain tied to what the void is doing structurally. Not every

crack needs to be filled, and not every filled crack needs to become stronger than the surrounding marble.

19.15. A Decision Rule for Adhesive Strength

The findings of the paper can now refine how adhesive strength should be used in selection. Rather than asking whether the adhesive is weaker than the stone, the practitioner should ask: **Does the system possess enough capacity for expected service, and if additional adhesive strength is available, does that additional capacity improve preservation or merely relocate failure into original material?** This rule retains strength as an engineering requirement while preventing it from becoming the sole definition of repair quality. It also provides a rational response when manufacturers advertise bonds stronger than stone. That characteristic may be useful. It is not automatically the characteristic conservation is trying to maximize.

19.16. A Decision Rule for Reversibility

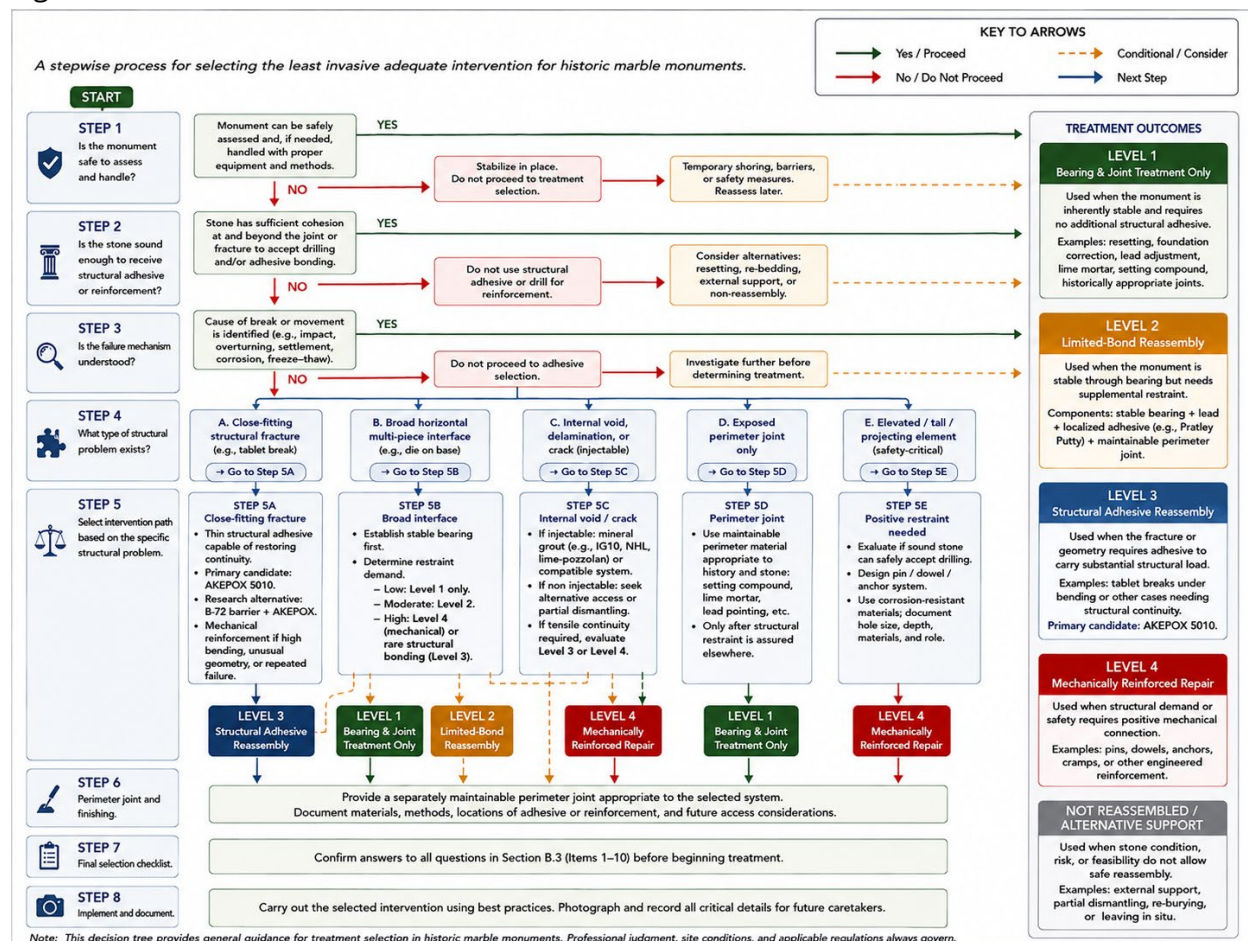
A parallel rule applies to reversibility: **Prefer the treatment that preserves the greatest practical future options without sacrificing the structural capacity required for present preservation.** This may favor B-72 in one repair and localized epoxy in another. It may favor reusing historic pin holes rather than drilling new ones. It may favor a replaceable lime perimeter over structural resin. It may occasionally favor no treatment. The criterion is practical future access, not adherence to an abstract material category. This approach aligns with both modern AIC treatment guidance and the longer conservation discussion of degrees of reversibility and retreatability.

19.17. Documentation as Part of Material Selection

Documentation should be considered part of the treatment system rather than an administrative task performed after repair. Permanent adhesive that is invisible after assembly becomes significantly less retreatable if future practitioners do not know where it was placed. A treatment record should therefore include product, formulation, batch where practical, mixing ratio, approximate quantities, adhesive locations, intervention layers, bearing locations, pin dimensions and materials, perimeter material, environmental conditions, photographs, and observations regarding stone condition. NPS documentation guidance emphasizes both written and photographic records and recognizes recurring condition assessment as essential to future preservation planning. A technically excellent repair without adequate records is less conservative because it removes information from the next person who must work on the monument.

The treatment-selection sequence developed throughout this chapter is consolidated in Figure 19.1. The decision tree begins with stone condition, failure diagnosis, monument configuration, and structural demand before moving toward adhesive or reinforcement selection, thereby keeping product choice subordinate to the conservation and structural problem being solved.

Figure 19.1 - Treatment-Selection Decision Tree



Note. This decision tree provides a general framework. Final treatment decisions must be based on a complete assessment of the stone, its condition, historical significance, and the skills and materials available. When in doubt, choose the least invasive option that achieves stability.

20. The Limited-Bond Reassembly Model

20.1. Defining the Model

The Gravestone Guardians limited-bond reassembly model can now be defined formally. It is a treatment philosophy for selected multi-piece historic stone monuments in which **primary dead load is carried through stable bearing, alignment is controlled through appropriate shimming or wedging, permanent structural adhesive is confined to limited locations providing supplemental restraint, and the exposed perimeter joint is treated independently using a maintainable material.** The model is intended primarily for monument configurations whose mass and geometry already provide substantial inherent stability. It is not proposed as a universal alternative to pinning, full structural bonding, mortar setting, or other recognized conservation methods. Its conservation rationale rests upon limiting the role and extent of irreversible material while maintaining adequate service stability.

20.2. The Four Functional Layers

The model divides the repair into four functional layers.

Foundation and primary support

The foundation, base, or lower monument component must first provide stable support. No adhesive system can compensate reliably for continuing settlement or defective foundation geometry.

Bearing and alignment

Stone-to-stone contact and appropriately positioned lead wedges or other compatible bearing materials establish level, plumb, joint spacing, and distribution of compressive load.

Localized structural restraint

Pratley Standard Setting Putty, or another adhesive demonstrated suitable for the particular application, is confined to selected areas intended primarily to resist sliding, rocking, separation, or accidental displacement.

Perimeter joint management

Monument setting compound, lime mortar, lead pointing, or another appropriate material closes and protects the exposed interface while remaining conceptually separate from the principal structural restraint.

This division of function differentiates the GG model from simply “gluing the monument together.”

20.3. Applicability

The model is most appropriate where several conditions coincide. The monument should consist of discrete components with broad horizontal or near-horizontal bearing surfaces. The lower support should be stable or capable of stabilization. The upper component should possess substantial gravitational stability. Sound marble should exist at the proposed adhesive locations. The expected restraint demand should be moderate rather than safety-critical. Future dismantling should remain feasible. Typical candidates include low or moderate-height die-and-base monuments, broad pedestal sections, caps, and similar stacked elements where historic stability derived substantially from mass and bearing. The model becomes progressively less suitable as the monument becomes taller, narrower, more top-heavy, more deteriorated, more heavily exposed to overturning, or more dependent upon positive tensile attachment. A system designed around limited adhesive should not be extended beyond the structural conditions that justify its restraint capacity. The limited-bond model is developed principally around historic marble, but its structural logic is not necessarily restricted to that material. Broad, compression-loaded granite monument assemblies may present similar opportunities to separate bearing, restraint, and perimeter-joint functions. Because granite typically differs substantially from weathered marble in substrate cohesion, porosity, stiffness, and moisture behavior, however, adhesive area, pad placement, required restraint, and anticipated failure mode should be evaluated independently. Application of the GG limited-bond model to granite should therefore be considered a related but separately testable treatment category.

20.4. Conditions That Exclude Routine Use

Several conditions should trigger reconsideration before the GG limited-bond method is used. Severe sugaring or cracking at the adhesive zones may leave insufficient cohesive marble. A substantially unstable foundation must be corrected first. A narrow or top-heavy component may require positive mechanical reinforcement. An elevated element whose release could injure visitors or destroy irreplaceable sculpture may warrant an engineered pin or anchor. Significant historical evidence of original mechanical reinforcement may justify repair or replacement of that system rather than substitution with localized adhesive. A bearing interface so damaged that the upper component cannot remain stable without thick masses of putty does not meet the model's central requirement for independent support. These exclusions are important because they prevent limited bonding from becoming a philosophical preference applied regardless of mechanics.

20.5. Step 1 — Document Before Disassembly or Treatment

The monument should be photographed comprehensively before work begins.

Photographs should include overall orientation, each visible joint, existing cracks, previous repairs, foundation condition, inscriptions and decorative elements, biological growth, displaced fragments, and any visible shims or metal.

Measurements should record component dimensions, joint width, tilt, displacement, and relevant foundation conditions.

Where a monument is already dismantled, the position and orientation of each fragment should be recorded.

This approach is consistent with NPS cemetery guidance, which emphasizes written and pictorial documentation of damage, fragments, construction materials, and treatments.

Documentation should continue throughout treatment, not merely before and after.

20.6. Step 2 — Diagnose the Failure

The practitioner should determine why the monument separated or became unstable.

If the failure resulted from deteriorated setting compound while the base remains level and sound, resetting may proceed relatively directly.

If frost, settlement, erosion, roots, corrosion, or prior inappropriate repairs caused the displacement, those conditions must be addressed before the monument is rigidly reassembled.

This step protects against the common error of creating a stronger upper joint while leaving the original source of movement active below.

A repaired monument should not be stronger merely in its ability to resist revealing the same unresolved problem.

20.7. Step 3 — Stabilize the Foundation and Lower Component

The lower component must be level, stable, and adequately supported before the next stone is placed.

Foundation repair falls outside the narrow adhesive scope of this paper but remains integral to the system.

No amount of Pratley, AKEPOX, lead, or setting compound can create a conservation-compatible upper joint if the lower component is continuing to rotate or settle.

The treatment record should therefore state explicitly whether foundation stabilization was performed, judged unnecessary, or referred for additional work.

20.8. Step 4 — Clean the Bearing Surfaces Conservatively

The bearing surfaces should be cleaned sufficiently to remove loose debris, biological material, failed setting compound, detached mortar, and incompatible residues that prevent accurate seating.

Cleaning should stop before original sound marble is unnecessarily altered.

Commercial adhesive instructions may recommend abrasive roughening to maximize adhesion, but such preparation should not be adopted automatically on historic stone. Natural fracture and weathered setting surfaces already contain substantial texture, and removal of original fabric solely to improve resin performance conflicts with minimum intervention.

The objective is a sound, uncontaminated interface—not newly fabricated stone.

20.9. Step 5 — Dry-Fit the Components

Dry fitting is mandatory to the logic of the limited-bond model.

The upper component should be lowered into position without structural adhesive so the team can determine how it naturally bears, whether it rocks, what joint width develops, where existing high points occur, and what adjustments are necessary.

If the component cannot achieve a stable position without large amounts of fill, the reason should be investigated.

Dry fitting also allows the practitioner to identify locations suitable for localized adhesive pads and areas that should be avoided because of edges, cracks, carvings, or deteriorated marble.

The adhesive strategy should emerge from what is learned during dry fitting.

20.10. Step 6 — Establish Stable Bearing

Lead wedges may be introduced at selected positions to refine level and joint spacing.

Their role should remain limited to adjustment and local load distribution. The component should not be intentionally supported only on several tiny lead points where broad stable bearing could otherwise be achieved.

The preferred condition is one in which the upper stone would remain stable and properly aligned even if the adhesive were absent. This is the mechanical heart of the GG model.

If removal of the adhesive would cause the upper component to drop, tilt, or lose its bearing position, the repair is no longer functioning as a limited-bond system.

20.11. Step 7 — Select Adhesive Locations

Adhesive locations should be planned rather than improvised during final setting.

Suitable locations should contain comparatively sound stone, adequate surrounding material, and sufficient setback from fragile edges.

Pads should generally be distributed so that they provide useful resistance to movement without creating a continuous structural perimeter.

Locations directly adjacent to severe cracks, carved recesses, thin projections, chipped corners, or sugared surfaces should be avoided.

The number, size, and precise geometry of pads cannot yet be prescribed quantitatively because the necessary experimental validation has not been completed.

Until such data exist, the governing principle should be **minimum bonded area consistent with the required restraint**.

20.12. Step 8 — Document the Adhesive Before Final Assembly

Before the upper component is lowered, the adhesive locations should be photographed.

A treatment diagram should record their approximate size and position relative to identifiable monument edges or features. This step materially improves future retreatability.

A conservator encountering the monument decades later should not have to discover hidden Pratley pads through destructive probing.

Permanent interventions become more responsible when their locations are made legible through records.

20.13. Step 9 — Apply the Localized Structural Adhesive

Pratley Standard Setting Putty currently serves as the principal GG material for this role because its mouldable consistency allows controlled discrete placement and adequate working time for monument setting.

The material should be mixed according to current manufacturer instructions and applied only in the predetermined locations.

It should not be spread progressively across the interface simply because excess material remains.

Additional adhesive is not automatically additional conservation.

The objective is to create enough restraint for the defined structural demand while preserving substantial unbonded historic interface.

20.14. Step 10 — Lower and Align the Component

The component should be lowered under controlled conditions using appropriate lifting equipment.

Final alignment should be checked in multiple directions while the adhesive remains workable.

Lead adjustments should be made gradually and without concentrating force against fragile edges.

The component should reach final bearing independently of curing adhesive.

Excess putty displaced toward the perimeter should be removed where safely accessible before cure, taking care not to smear resin across exposed historic marble.

The repair should not be considered correctly seated simply because adhesive fills the joint.

20.15. Step 11 — Treat the Perimeter Independently

Once bearing and structural restraint are established, the exposed joint should be closed using the material selected for perimeter performance.

For some monuments this may be monument setting compound.

For others, historical evidence or stone condition may favor lime-based mortar or lead pointing.

The perimeter material should not be assumed to provide the primary structural connection.

Its expected maintenance life may be shorter than that of the concealed adhesive, and future renewal should remain possible without dismantling the monument.

This functional independence is one of the model's principal conservation advantages.

20.16. Step 12 — Allow Proper Cure and Protect the Repair

The assembly should remain undisturbed during the required cure period for the structural adhesive and any hydraulic perimeter materials.

Temperature, precipitation, and moisture conditions should be considered in scheduling.

Manufacturer minimum cure times should not be interpreted as evidence that maximum long-term properties have developed immediately.

Where temporary bracing or restraint is required, it should be arranged so that the stone is protected from abrasion and point loading.

The monument should not be subjected to cleaning, heavy handling, or other work that unnecessarily disturbs the joint during early cure.

20.17. Step 13 — Final Documentation

The final treatment record should include:

- monument identification and location;
- date of treatment;
- personnel;
- condition before treatment;
- probable failure cause;
- foundation work;
- bearing observations;
- lead locations;
- structural adhesive product and formulation;
- approximate adhesive pad locations and dimensions;
- perimeter material;
- photographs before, during, and after assembly;
- weather and curing conditions; and
- recommendations for monitoring.

This is one of the situations where a structured list is justified because the record itself serves as a field reference.

AIC ethics place explicit importance on complete written and pictorial documentation of examination and treatment.

20.18. Monitoring the Limited-Bond System

The treatment should not be judged complete at the moment the lifting equipment is removed. Monitoring should examine joint width, tilt, perimeter condition, cracking, staining, lead extrusion, edge crushing, movement, and changes in neighboring stone. A useful schedule would include inspection after the first seasonal cycle, approximately one year after treatment, and at longer intervals thereafter depending upon monument significance and exposure. NPS guidance recommends recurring condition assessment because deterioration and structural conditions change over time. For experimental or early-generation GG limited-bond repairs, monitoring should be more frequent because field observations can inform refinement of the method.

20.19. What the GG Model Does Not Claim

For the methodology to remain technically credible, its limitations should be stated as clearly as its advantages. The GG model does **not** claim that Pratley Standard Setting Putty is weaker than historic marble. It does not claim that localized adhesive will always fail before stone. It does not claim that pinning is inappropriate. It does not claim that every multi-piece monument can be safely stabilized without mechanical reinforcement. It does not claim that monument setting compound is universally preferable to lime mortar. It does not claim that lead wedges eliminate the need for broad stable bearing. It does not claim that a permanent adhesive becomes chemically reversible merely because less of it is used. What the model claims is narrower and more defensible: **where a monument is inherently stable through geometry and compression, permanent adhesive can potentially be restricted to the amount needed for supplemental restraint, thereby reducing invasive drilling and limiting the area of historic stone committed to irreversible bonding.** That proposition remains experimentally testable.

20.20. Why the Model May Represent a Conservation Middle Ground

Traditional conservation criticism of strong adhesives focuses heavily on permanence, excessive stiffness, and the possibility of transferring failure into original marble. Monument-industry practice often prioritizes durable permanent attachment and resistance to movement. The GG model attempts to preserve the strongest logic of both positions. It accepts the conservation argument that unnecessary permanent bonding and

drilling should be avoided. It also accepts the practical monument-setting requirement that reassembled components must possess adequate resistance to movement and cannot depend upon deliberately fragile joints. The middle ground is created not by finding an adhesive of mathematically perfect intermediate strength but by **controlling the structural role of the adhesive itself**.

Gravity carries gravity. Bearing carries compression. Lead refines bearing. Adhesive restrains movement. The perimeter joint manages exposure. Pins are reserved for conditions requiring positive mechanical reinforcement. Each material performs a defined function rather than one product being expected to solve the entire monument.

20.21. Relationship to Minimum Intervention

Minimum intervention is sometimes misunderstood as minimum material quantity regardless of outcome. A more useful interpretation is the minimum permanent alteration necessary to achieve adequate preservation. Under that definition, using several localized adhesive pads may represent less intervention than drilling new dowel holes into sound marble. In another monument, a carefully engineered pin may represent less overall intervention than coating an entire broad interface with structural epoxy. A third monument may require neither. The GG model therefore should not become a new universal recipe replacing older universal recipes. Its strongest conservation principle is the requirement to justify each structural intervention separately.

20.22. Relationship to Reversibility and Retreatability

The model remains only partially reversible. Pratley Putty is a permanent thermosetting material. Where it bonds directly to marble, exact restoration of the original untreated surface is unlikely. Its potential advantage lies in **retreatability through geometry**. Because only selected locations are bonded, a future practitioner may be able to open the perimeter, lift or progressively separate the component, and address the remaining adhesive locally. This advantage becomes substantially stronger if future research demonstrates that a B-72 intervention layer can be used beneath Pratley without compromising service capacity or exterior durability. Such a system could combine independent bearing, limited permanent adhesive area, and a chemically weakenable interface beneath the permanent putty. That remains one of the highest-value experimental questions emerging from this paper.

20.23. Relationship to Failure Hierarchy

The GG model can now be expressed as an intended failure hierarchy. Under ordinary conditions, the monument remains stable through bearing, mass, friction, and localized

restraint. With normal aging, the exposed perimeter material may deteriorate first and be renewed. If minor movement occurs, changes in the perimeter joint may provide visible evidence before major stone failure. Under greater lateral force, friction is overcome and the adhesive pads begin carrying increasing restraint. If load continues beyond the system's intended capacity, localized adhesive release or limited local stone failure is preferable to widespread fracture of the monument. Under loads sufficiently severe to overturn or destroy the monument regardless of treatment, no adhesive strategy can guarantee preservation. The value of the model depends upon whether experimental testing confirms that this hierarchy actually develops. Until then, it should remain an explicitly stated design hypothesis rather than a presumed fact.

20.24. Proposed Treatment Categories

For internal practice, the findings of Chapters 18–20 suggest four levels of structural intervention.

Level 1 — Bearing and Joint Treatment Only

Used where the monument possesses adequate inherent stability and requires no additional structural adhesive.

Treatment may include foundation correction, resetting, lead adjustment, lime mortar, setting compound, or historically appropriate joint work.

Level 2 — Limited-Bond Reassembly

Used where the monument is independently stable but benefits from supplemental restraint.

Stable bearing is combined with localized adhesive and a separately maintainable perimeter joint.

Level 3 — Structural Adhesive Reassembly

Used where the fracture or geometry requires adhesive to transmit substantial structural load, as in suitable tablet fractures.

AKEPOX 5010 or another validated structural adhesive may provide the principal connection.

Level 4 — Mechanically Reinforced Repair

Used where structural demand, geometry, or safety requires pins, dowels, anchors, or another positive mechanical connection.

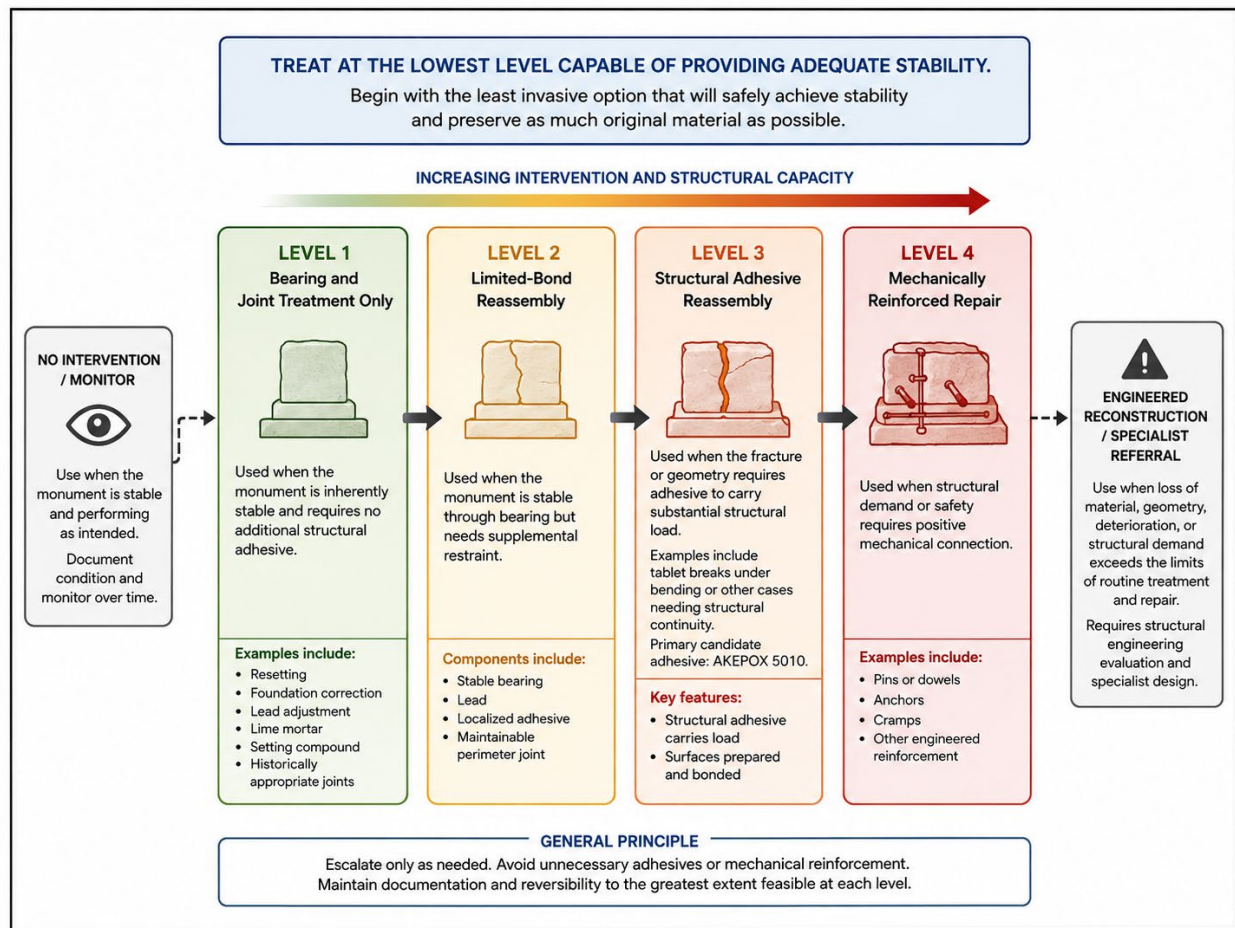
The reinforcement should be designed and located according to stone condition and expected load rather than applied by default.

These categories create a progression from least to most structurally invasive intervention without assuming that every monument should advance through the sequence.

The correct level is the first one capable of providing adequate preservation and safety.

Figure 20.1 places the four treatment categories proposed in this paper along a progressively more invasive structural continuum. The hierarchy is not intended to imply that a higher level is superior; rather, treatment should remain at the lowest level capable of providing adequate stability for the particular monument and its foreseeable loading.

Figure 20.1: Levels of Structural Intervention



Note. Select the lowest level of intervention that safely achieves stability and preserves as much original material as possible. Higher levels involve greater invasiveness, lower reversibility, and higher risk of future complications.

20.25. Proposed Stop Criteria

A corresponding set of **stop criteria** should prevent field enthusiasm from pushing a repair beyond what the stone can safely support. Work should pause for reassessment where the substrate proves substantially weaker than expected, hidden cracks become visible, bearing cannot be restored, the monument remains unstable without adhesive, required pad area expands substantially beyond the intended limited-bond configuration, drilling appears necessary despite inadequate edge distance, significant foundation movement is discovered, or the structural consequence of release exceeds the competence of the planned repair. Stopping work under those conditions is not failure. It is application of the same minimum-intervention principle that governs material selection.

20.26. Relationship to Professional Conservation Standards

The GG model is consistent with broader professional conservation principles to the extent that it emphasizes examination, documentation, minimum necessary intervention, treatment suitability, future treatment, and preservation of original material. AIC guidance states that treatment should be selected according to the specific cultural property and that its benefits must be weighed against potential adverse consequences for future treatment and function. NPS cemetery guidance similarly emphasizes cyclical, noninvasive, preservation-minded care; thorough condition assessment; documentation; and treatment appropriate to the monument and its environment. Those standards do not specifically validate Pratley Standard Setting Putty, Akepox 5010, or the GG pad geometry. They validate the **decision principles** against which those materials should be tested. That distinction should remain clear throughout the final paper.

20.27. From Working Method to Testable Methodology

The most significant development in formalizing the GG model is that the method can now be described in variables that can be tested. The relevant variables include bonded area, pad size, pad location, pad thickness, bearing distribution, joint width, marble condition, component geometry, adhesive formulation, use of intervention layers, environmental aging, and load direction. The outcomes can likewise be measured: initial movement, ultimate load, stiffness, displacement, stone loss, failure location, retreatability, moisture response, and long-term alignment. This transforms an experienced field practice into a research hypothesis. Instead of asking whether monuments reset with Pratley and lead “seem to hold,” the experimental question becomes: **Does stable bearing combined with deliberately limited adhesive restraint provide adequate service capacity while reducing irreversible stone involvement and the severity of eventual failure compared with continuous structural bonding or unnecessary pinning?** That is a question capable of producing evidence.

20.28. Preliminary Gravestone Guardians Position

On the evidence currently available, Gravestone Guardians can reasonably articulate the following provisional position: Historic marble monument repair should employ the least invasive structural system capable of providing adequate stability. Adhesive strength alone does not determine compatibility, and neither epoxy nor pinning should be used automatically simply because either creates a stronger joint. For closely fitting tablet fractures in marble with adequate cohesive strength, a carefully controlled structural epoxy bond may represent a proportionate intervention when compared with drilling and reinforcement. For broad multi-piece monument interfaces that are inherently stable

through mass, geometry, and compression, stable bearing combined with limited localized adhesive restraint and a separately maintainable perimeter joint offers a plausible conservation-oriented alternative to full-surface bonding or routine pinning. Where structural geometry requires positive mechanical reinforcement, pinning remains an appropriate and sometimes necessary treatment. Where stone condition cannot safely support any of these interventions, treatment should become less—not more—aggressive. The GG model therefore does not seek the strongest possible repaired monument. It seeks a monument that is **strong enough to remain stable, minimally altered enough to preserve historic fabric, understandable enough to be retreated, and deliberately designed so that modern repair materials do not unnecessarily determine where the historic stone will fail next.**

21. Limitations of Existing Adhesive Research

21.1. The Evidence Is Useful but Incomplete

The preceding chapters draw upon conservation research, materials science, manufacturer technical data, monument-setting practice, and established conservation principles. Together, these sources provide enough evidence to reject simplistic rules such as “strong adhesives should never be used on historic marble” or, conversely, “the strongest bond is always the best repair.” They do not yet provide enough evidence to identify one structural adhesive system as universally preferable for exterior historic marble.

This distinction is important. The absence of conclusive evidence does not make every material choice equally defensible. Some systems are supported more strongly than others by material properties, conservation precedent, manufacturer guidance, or structural logic. AKEPOX 5010, for example, is specifically formulated for durable natural-stone bonding and has characteristics appropriate to thin exterior joints. Paraloid B-72 has an exceptionally well-developed conservation history and published marble-testing literature. Mineral injection grouts have undergone extensive conservation-specific methodological study. These are meaningful advantages.

The remaining uncertainty arises because the central question of this paper is more specific than most existing research: **How do different adhesive and reassembly systems behave when used on naturally or artificially weathered exterior marble, and which system provides adequate structural performance while producing the least damaging failure and the greatest practical retreatability?** Very few published studies answer all parts of that question simultaneously.

21.2. Much Adhesive Testing Was Designed for Different Industries

Standard adhesive testing is essential to materials engineering, but many established methods were developed around substrates and applications substantially different from historic marble conservation.

ASTM D1002, for example, is specifically designed to determine the apparent shear strength of adhesively bonded metal single-lap joints. The geometry, surface preparation, substrate homogeneity, and loading of such specimens differ substantially from a naturally fractured marble tablet or weathered monument interface.

Podany and colleagues recognized this problem in their marble adhesive research. Their tensile evaluation drew upon ASTM D2095 but was modified to accommodate marble substrates and to maintain the alignment necessary for meaningful stone testing. The significance of that decision extends beyond the particular study. A recognized standard can provide useful loading concepts, instrumentation, reporting procedures, and repeatability without reproducing the conservation problem exactly.

The Getty Conservation Institute reached a similar conclusion during its injection-grout research. Existing ASTM, EN, DIN, UNI, and related methods had generally been developed for conventional mortars, Portland-cement systems, or other construction materials rather than lime-based conservation grouts. Getty researchers consequently evaluated, modified, and in some cases developed new procedures appropriate to the materials and conservation functions under study.

Technical Paper No. 3 should follow the same methodological principle. Standardized tests should inform the experimental design, but a test should be selected because it helps answer the conservation question—not simply because it carries an ASTM or EN designation.

21.3. Laboratory Marble Is Usually Better Than Cemetery Marble

One of the largest limitations of existing adhesive studies is the condition of the stone being tested.

Controlled laboratory experiments require specimens of reasonably consistent geometry and material properties. Researchers therefore commonly use freshly quarried or commercially available marble. Jorjani and colleagues, for example, used Carrara marble in their comparative study of eight thermoplastic and thermosetting adhesive systems.

Such specimens are appropriate for comparative materials research because they reduce uncontrolled variation. They do not reproduce the condition of a marble headstone that has spent 150 years outdoors.

Weathered marble can contain intergranular microcracks, increased porosity, weakened grain boundaries, previous freeze-thaw damage, salts, moisture, biological residues, previous treatments, and localized granular disintegration. Research on marble deterioration shows that progressive weathering can substantially reduce ultrasonic velocity and dynamic Young's modulus while increasing crack development and water uptake. In one extensive study of multiple marble types, artificial weathering produced major reductions in dynamic modulus, with the degree of change strongly dependent upon marble fabric.

The implication for adhesive research is substantial. A resin system that causes cohesive failure in fresh Carrara marble may produce the same type of failure at a much lower load in naturally weathered cemetery marble. More importantly, different adhesive systems that appear similarly strong on sound stone may diverge considerably once the substrate becomes the mechanically limiting material.

Fresh marble therefore provides an important control condition. It should not be the only condition.

21.4. “Weathered Marble” Is Not One Reproducible Material

Introducing deteriorated marble into an experiment creates another problem: weathering itself is highly variable.

Marble deterioration depends upon mineralogy, grain size, grain-boundary geometry, crystallographic preferred orientation, moisture history, thermal exposure, freeze-thaw cycles, structural loading, and previous damage. Calcite's anisotropic thermal expansion produces internal incompatibility among differently oriented grains, but the resulting deterioration varies substantially among marble fabrics.

Two nineteenth-century marble monuments of similar appearance and age can therefore possess very different mechanical properties. Naturally weathered specimens provide realism but reduce experimental uniformity. Artificially weathered specimens provide greater control but simplify the complexity of long-term natural deterioration. A credible experimental program should use both. Artificial weathering can create graded and reproducible changes in a known marble. Naturally weathered sacrificial material can then test whether conclusions derived from laboratory aging remain plausible under authentic historic deterioration. Neither specimen population should be allowed to substitute entirely for the other.

21.5. Marble Orientation Is Frequently Underappreciated

Marble is not isotropic. Its mechanical and thermal properties can vary according to grain fabric and orientation. Research evaluating marble weathering through ultrasonic velocity and thermal expansion specifically records measurements in multiple directions because crack distribution, wave velocity, thermal dilation, and elastic behavior can be directionally dependent. This creates a potentially important source of experimental scatter. If specimens for different adhesives are cut randomly from a marble slab without tracking orientation, apparent differences between adhesive systems may partly reflect differences in stone fabric. Experimental specimens should therefore be produced from a well-documented parent material where possible. Orientation should remain consistent across

comparison groups, or specimens should be randomized systematically so that orientation effects are distributed among treatments. The same consideration applies to naturally weathered material. If original quarry orientation is unknown, that uncertainty should be recorded rather than ignored.

21.6. Most Studies Examine Adhesives, Not Monument Systems

Published marble adhesive research has generally focused upon bonded specimens designed to isolate adhesive behavior. That work is necessary. Podany's tensile and shear specimens demonstrated that epoxy, polyester, and B-72 systems could all develop sufficient capacity for cohesive marble failure under certain conditions. Jorjani's work added interfacial fracture toughness and bond-line width to the evaluation. Neither study was designed specifically to evaluate a multi-piece cemetery monument in which stone bearing, lead wedges, adhesive pads, friction, and perimeter setting material work together. That distinction is fundamental to the Gravestone Guardians hypothesis. The GG limited-bond model does not propose Pratley Standard Setting Putty as a direct one-for-one replacement for a continuous epoxy bond. It proposes a different structural system in which the adhesive performs less of the work. Testing Pratley and AKEPOX as simple equal-area adhesive coupons would therefore provide useful material information while failing to test the central proposition. Both **material-scale** and **system-scale** testing are required.

21.7. Published Research Rarely Treats Bonded Area as an Independent Conservation Variable

Bond-line thickness has received meaningful attention in conservation adhesive research. Bonded surface area, particularly the deliberate reduction of bonded area as a conservation strategy, has received much less systematic study.

This is surprising because area has direct mechanical and conservation consequences.

The same adhesive covering an entire monument interface and occupying four small internal pads creates substantially different total bonding, moisture barriers, retreatment requirements, and load-transfer geometry.

Limited bonding therefore deserves to be tested as an independent experimental variable rather than being treated as an application technique.

Relevant comparison groups should include identical adhesives used at different percentages of available interface area.

The purpose would not be to calculate a universal percentage of “safe bonding.” Such a number would be misleading because monument geometry and loading vary.

The purpose is to establish the direction and magnitude of the relationship between reduced adhesive area, service capacity, failure location, and stone loss.

21.8. Full Structural Strength Is Commonly Measured; Damage Severity Is Not

Engineering adhesive tests naturally emphasize load capacity.

Maximum tensile stress, shear strength, flexural capacity, bond strength, and fracture toughness provide essential information. They tell the researcher whether a joint can carry useful structural loads and permit quantitative comparison among systems.

They do not fully describe conservation performance.

Podany's finding that multiple adhesives caused the marble to fail first is highly important precisely because the **location** of failure provides information that maximum stress alone cannot.

Even failure location remains incomplete if simply divided into “adhesive” and “stone.”

A specimen losing several superficial grains and one that develops a deep secondary fracture might both be categorized as cohesive stone failure.

Their conservation consequences are dramatically different.

Future testing should therefore quantify stone damage rather than merely identify its presence.

21.9. Long-Term Sustained Loading Is Poorly Represented

Many conventional adhesive tests increase load continuously until failure. This provides a convenient and repeatable measurement of ultimate capacity.

Historic monuments do not usually experience loads in that manner.

Much of their structural demand is persistent and comparatively low: dead load, small eccentricities, modest shear, and repeated environmental movement. Occasionally, a much larger transient load may occur through vandalism, impact, falling vegetation, handling, or severe weather. Polymers can behave differently under sustained stress than they do during a short mechanical test. Thermoplastic materials are particularly susceptible to creep as temperature rises, but thermosetting polymers and composite systems can also exhibit time-dependent behavior. Lead wedges likewise creep under sustained compression. A repair system should therefore not be evaluated solely by how

much force it survives over several minutes. Long-duration load retention and displacement deserve separate evaluation.

21.10. Laboratory Temperature Does Not Reproduce Cemetery Temperature

Many adhesive data sheets and laboratory experiments report properties around conventional room temperature. Exterior marble experiences a much broader range. Direct solar radiation can heat the stone above ambient air temperature. Winter conditions can expose it to prolonged freezing. Daily cycles repeatedly move the adhesive and marble through changing temperature and moisture conditions. This matters because polymer stiffness, creep, glass-transition behavior, and thermal expansion are temperature dependent. B-72 provides an especially clear example. Its thermoplastic behavior becomes increasingly relevant as temperature approaches its glass-transition region, and residual solvent can depress that transition dramatically. Outdoor structural evaluation must therefore consider actual service temperature rather than assuming that room-temperature laboratory behavior is sufficient. Marble itself also changes through thermal cycling. Research has repeatedly demonstrated that heating and cooling can increase microcracking and reduce elastic properties. The repaired joint is consequently a coupled system in which both adhesive and substrate change with exposure.

21.11. Accelerated Aging Is Not Equivalent to Natural Aging

Accelerated aging is necessary because conservation research cannot wait several decades before evaluating a repair. Yet accelerating deterioration inevitably changes the experiment. Increasing temperature, ultraviolet intensity, salt concentration, or cycling frequency can activate mechanisms more aggressively than they occur naturally. Some accelerated protocols may even produce damage mechanisms unlikely to dominate in the field. Natural-stone salt testing provides a useful example. EN 12370-based procedures can expose stone to concentrated sodium sulfate and high drying temperatures. Researchers attempting to approximate more realistic environmental conditions have modified both salt concentration and drying temperature because standard protocols can impose unusually severe conditions. Accelerated aging should therefore be used comparatively. If System A deteriorates more rapidly than System B under the same controlled exposure, the result is meaningful. The experiment should not claim that twenty laboratory cycles are literally equivalent to a specified number of cemetery winters unless an independent validated relationship exists.

21.12. Freeze-Thaw Standards Remain an Imperfect Fit

Freeze-thaw testing presents a similar methodological challenge. ASTM has specifically acknowledged limitations in applying ASTM C666, originally developed for concrete, to natural stone. A current ASTM work item notes that the concrete procedure does not address several characteristics unique to dimension stone and seeks a more appropriate test for evaluating changes in natural-stone mechanical properties after rapid freezing and thawing. This is highly relevant to the proposed research. Using an established freeze-thaw procedure without adaptation could provide reproducible cycling while falsely implying that the test is validated specifically for historic marble adhesive assemblies. The better approach is to design a documented conservation test informed by natural-stone standards and climate conditions, measure change before and after exposure, and report the protocol transparently. The resulting evidence can then be reproduced or challenged by others.

21.13. Moisture Transport Is Often Separated from Mechanical Testing

Structural adhesive research and stone-moisture research are frequently conducted as separate subjects. Historic monuments do not experience them separately. A strong adhesive layer may alter local water transport. The stone may weather differently beside the bond. An intervention layer intended to increase reversibility may also change vapor or liquid-water movement. Studies of polymer-treated outdoor stone demonstrate that weathering behavior can include chemical, optical, and physical changes under photo-oxidative and saline exposure. The proposed experimental program should therefore include basic hydric observations in addition to mechanical strength. It need not become a complete hygrothermal study of every adhesive formulation. It should at minimum determine whether different repair configurations create conspicuous changes in water uptake, drying, staining, or moisture concentration around the joint.

21.14. Retreatability Testing Is Rare

Conservation literature discusses reversibility extensively, but relatively few structural studies actually dismantle aged repaired specimens and quantify what happens. Podany's B-72 barrier research is a notable exception because strength and reversibility were deliberately evaluated together. This combined approach should become central to Technical Paper No. 3. A repair cannot be described meaningfully as more retreatable merely because one resin is theoretically soluble or because adhesive pads occupy less surface area. The specimens should actually be taken apart after aging. Researchers should record how much time and intervention are required, what methods are needed, whether fracture surfaces survive, how much residue remains, and how much marble is

lost during separation. Retreatability should become an observed property of the completed repair rather than an assumption based on material chemistry.

21.15. Manufacturer Data Are Not Directly Comparable

Manufacturer technical sheets remain indispensable because they identify intended use, mixing ratios, cure conditions, working time, environmental limitations, and selected mechanical properties. They are not designed to function as a conservation comparison database. Different manufacturers report tensile strength, lap shear, flexural strength, hardness, elongation, modulus, peel strength, or “adhesion” under different standards and specimen conditions. Some provide extensive mechanical data; others provide little more than qualitative descriptions.

Comparing a 30 MPa bulk tensile result for one epoxy with a 15 MPa adhesion value from another product can therefore imply a precision that the test methods do not support. Technical Paper No. 3 should continue to report manufacturer data accurately while distinguishing them from results obtained through a common experimental method. The proposed program offers an opportunity to place several products into the **same specimen geometry, substrate, conditioning history, and test apparatus**. That will provide a more meaningful comparison than juxtaposing unrelated data-sheet numbers.

21.16. Field Practice Is Poorly Documented Scientifically

Monument setters and cemetery preservation practitioners possess substantial accumulated experience with Pratley Putty, monument setting compounds, lead wedges, epoxies, mortars, pins, and related systems. Much of that knowledge exists through training, oral tradition, practitioner networks, manufacturer instruction, and observations of repairs in service. It rarely exists as controlled published research. This does not make field experience scientifically worthless. Long-performing monuments constitute evidence.

Repeated patterns of success or failure can identify important questions that laboratory researchers might otherwise overlook. Field observation becomes much stronger evidence when it is documented consistently. Technical Paper No. 3 should therefore encourage systematic monitoring of actual GG repairs alongside formal laboratory experimentation. The laboratory explains mechanisms. The cemetery tests whether those mechanisms remain important in the real environment.

21.17. The Research Gap

The principal research gap can now be stated more precisely. Existing literature establishes that thermoplastic and thermosetting adhesives can provide substantial marble-bond capacity; that cohesive marble failure can occur with both “reversible” and irreversible

systems; that fracture toughness and bond-line dimensions matter; that weathering substantially changes marble mechanical properties; and that conservation test procedures frequently require modification of conventional standards. What remains inadequately established is the comparative performance of **complete monument-repair systems** using weathered marble under realistic environmental exposure. That gap provides the justification for the experimental program proposed in Chapter 22.

22. Proposed Experimental Program

22.1. Purpose

The experimental program proposed here is intended to evaluate the principal material and structural hypotheses developed throughout Technical Paper No. 3.

Its purpose is not to determine which adhesive possesses the highest possible strength.

The program instead asks four related questions:

First, which systems provide adequate structural capacity for the monument configurations they are intended to repair?

Second, how does weathering of the marble alter that performance?

Third, where and how severely does each system fail after mechanical and environmental loading?

Fourth, how readily can each system be retreated after aging?

These questions require a staged experimental design rather than one universal strength test.

22.2. Primary Hypotheses

The program should test several explicit hypotheses.

The first is that **marble condition will influence failure behavior more strongly as adhesive capacity exceeds substrate cohesion**. Strong thermosetting systems are expected to show increasingly substrate-dominated failure as marble deterioration progresses.

The second is that **reducing bonded area will reduce total restraint capacity but may also reduce the volume and severity of original stone loss during overload**, provided adhesive pads are positioned in sound substrate and stable bearing is maintained.

The third is that **stable bearing combined with localized structural restraint will provide sufficient service capacity for selected broad, compression-loaded monument geometries without reproducing the ultimate strength of continuous bonding**.

The fourth is that **B-72 intervention layers will improve practical retreatability beneath structural adhesives but may not cause preferential mechanical failure at the intervention layer**.

The fifth is that **mineral grouts will perform most favorably in void-filling and wider distributed-joint geometries rather than in very thin, highly tensioned tablet fractures.**

The sixth is that **environmental aging will alter both mechanical capacity and failure mode and that the degree of change will differ among adhesive systems.**

Each hypothesis can be falsified. That characteristic is essential if the testing is to function as research rather than as demonstration of a predetermined GG treatment preference.

22.3. A Tiered Research Design

A practical research program should proceed through four principal experimental tiers.

Tier 1 characterizes the marble and basic adhesive-joint behavior.

Tier 2 examines fracture geometries representative of tablet repair.

Tier 3 evaluates scaled multi-piece monument reassembly systems.

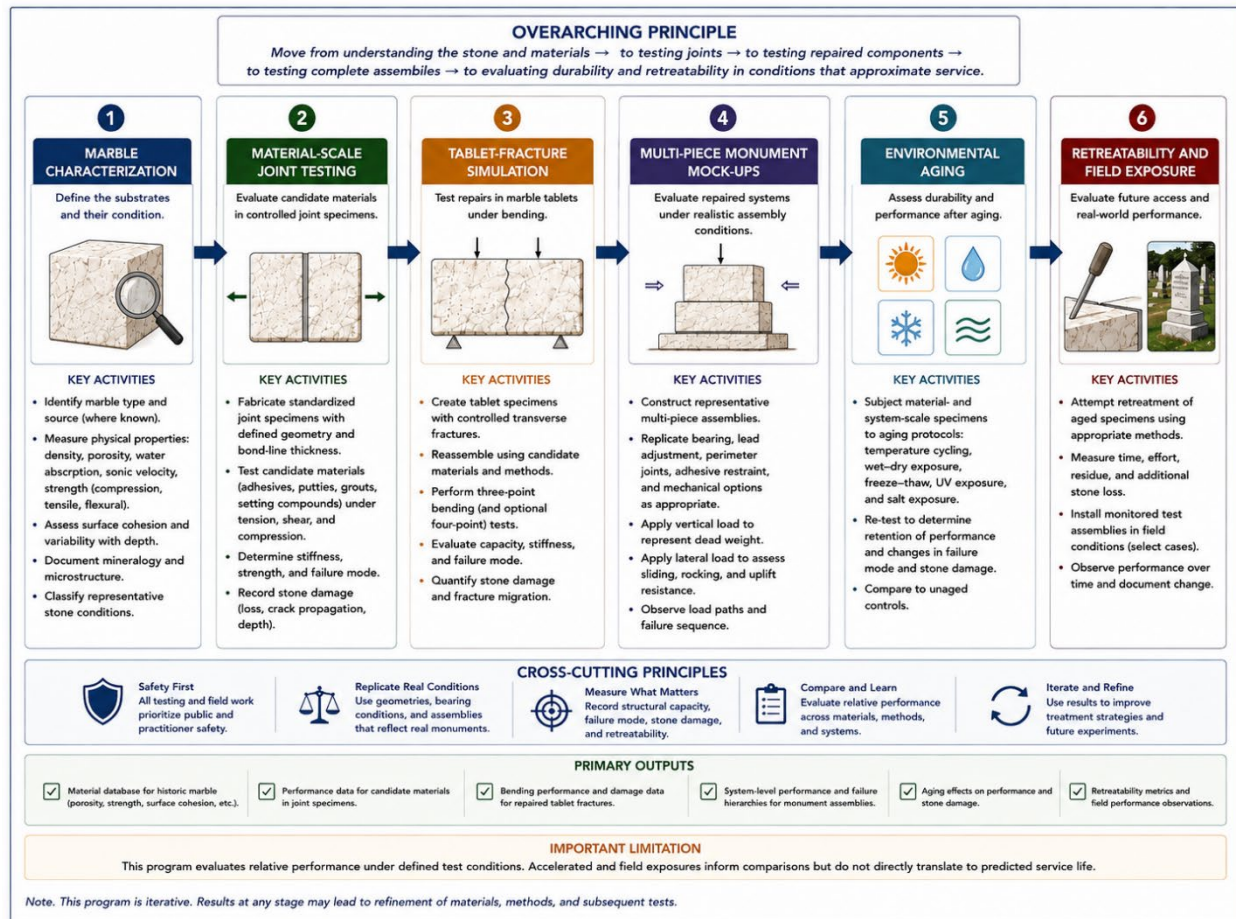
Tier 4 subjects selected systems to environmental aging and retreatability testing.

A fifth long-duration field-exposure program can operate in parallel once laboratory specimens have identified the most informative systems.

This staged design prevents resources from being consumed testing every material in every possible geometry. Poor-performing or clearly inappropriate candidates can be eliminated before the more expensive system-level tests.

The proposed research sequence is summarized in Figure 22.1. The program moves from substrate and material characterization through repaired-joint and monument-system testing, environmental aging, failure analysis, retreatability evaluation, and field correlation so that material performance can be assessed within progressively more realistic conservation conditions.

Figure 22.1: Proposed Experimental Program



Note. This proposed program is iterative. Results at any stage may inform refinement of materials, methods, and subsequent tests. Accelerated and field exposures support comparative evaluation but do not directly predict service life.

22.4. Specimen Marble

At least three marble conditions should be represented.

Condition A — Sound reference marble

Fresh, commercially available marble from a documented lot provides the controlled baseline.

Carrara marble would offer useful comparability with previous conservation literature, although a North American calcitic marble representative of common nineteenth-century cemetery material could also be included if reliably sourced.

Specimens should come from as few parent slabs as practical. Orientation should be documented.

Condition B — Artificially weathered marble

Specimens from the same parent material should be subjected to controlled weathering sufficient to produce measurable loss of stiffness and increased microcracking without reducing the stone to complete disaggregation.

Ultrasonic P-wave velocity provides one promising nondestructive method of tracking this degradation. Research has demonstrated a strong relationship between decreasing ultrasonic velocity, increased microcracking, and the weathering state of marble.

Artificially weathered specimens would provide a reproducible “weakened” substrate while retaining known stone provenance.

Condition C — Naturally weathered sacrificial marble

Where ethically and legally available, naturally weathered marble from nonhistoric discard material, broken replacement stock, documented architectural waste, or fragments already removed from cultural significance could provide a realistic comparison.

No intact historic grave marker or culturally significant fragment should be sacrificed for destructive experimental testing.

Naturally weathered specimens will introduce greater variability, but that variability is itself representative of cemetery practice.

22.5. Baseline Marble Characterization

Before bonding, each specimen population should be characterized sufficiently to establish that differences in later performance are not being attributed blindly to the adhesive.

At minimum, measurements should include mass, dimensions, visible condition, water absorption or capillary uptake where appropriate, and ultrasonic P-wave velocity.

Where laboratory access permits, additional characterization could include dynamic modulus, open porosity, petrographic examination, microscopy, and thermal-dilation measurements.

The purpose is not to generate a complete geological description of every sample.

It is to identify whether treatment groups begin with reasonably comparable substrate conditions and to quantify the degree of artificial weathering.

22.6. Tier 1 — Basic Joint Characterization

Tier 1 should use relatively simple marble-to-marble specimens to establish comparative behavior under common loading.

The exact specimen geometry should be developed with a qualified materials-testing laboratory. Podany's modified ASTM tensile work and Jorjani's fracture-toughness approach provide useful conservation precedents rather than mandatory templates.

Tests should include at least tensile or splitting behavior and shear behavior because monument joints encounter both.

The value of Tier 1 lies in placing all candidate materials into the same comparative framework.

22.7. Initial Adhesive Groups

A practical first-stage material set would include:

- Akepox 5010;
- Pratley Standard Setting Putty;
- Tenax Domo 10;
- Paraloid B-72 structural formulation;
- B-72 intervention layer + Akepox 5010;
- B-72 intervention layer + Pratley Standard Setting Putty;
- IG10 in a geometry appropriate to its intended crack width;
- one conventional polyester stone mastic as an industry comparison.

HXTAL NYL-1 and B-48N/B-72 blends could be added as secondary conservation benchmarks if resources permit. The experiment should not become so large that meaningful replication is sacrificed merely to include every interesting product. A smaller number of well-replicated systems will provide more useful evidence than a broad product catalog tested only once or twice.

22.8. Replication

Replicate specimens are essential because stone variability can be considerable even within one slab.

For preliminary screening, a minimum of approximately six specimens per material-condition combination would provide enough data to identify large differences and obvious variability.

Confirmatory testing of the most important comparisons should use larger groups, potentially ten to twelve or more specimens per condition where resources allow.

The final number should be established through statistical power analysis once pilot variability is known.

This is an important methodological point. Sample size should be driven by the variability of the system being measured rather than by an arbitrary convention.

22.9. Randomization and Blinding

Specimens should be assigned randomly to treatment groups after initial characterization so that naturally stronger or weaker samples are not unintentionally concentrated in one adhesive group.

Where practical, the person classifying post-failure stone damage should not know which adhesive was used until the damage classification has been recorded.

Complete blinding will be difficult because adhesive appearance may reveal the treatment, but even partial separation between treatment application and damage scoring can reduce unconscious bias.

This is especially important because Gravestone Guardians has an existing working preference for Akepox 5010 and limited Pratley systems.

A credible experimental program must be capable of producing results unfavorable to current GRAVESTONE GUARDIANS practice.

22.10. Surface Preparation

Surface preparation should reflect conservation practice rather than manufacturer maximum-bond protocols.

Historic fracture surfaces should not be ground or aggressively roughened simply because commercial fabrication instructions recommend abrasion.

For laboratory specimens, two geometries may be useful.

One series can use standardized cut surfaces to reduce variability and compare adhesive behavior.

A second series should use mechanically fractured marble surfaces that more closely reproduce authentic tablet breaks.

The difference between those series may itself provide useful evidence regarding the effect of natural fracture topography.

Cleaning procedures, moisture condition, and any solvent use should be identical across relevant comparison groups and fully documented.

22.11. Bond-Line Control

Bond-line thickness should be measured rather than estimated whenever possible.

Thin adhesive systems such as Akepox 5010 and B-72 should be tested at bond widths representative of close-fitting fracture repair.

Putty specimens should use thicknesses representative of actual GRAVESTONE GUARDIANS localized-pad practice.

IG10 should be tested only in geometries within a defensible working range for mineral grout. It should not be artificially forced into an impossibly narrow joint merely to create a direct material competition with epoxy.

Jorjani's research demonstrates why bond-line dimensions deserve direct measurement rather than treatment as an incidental variable.

22.12. Cure Conditions

All specimens should receive full cure under documented temperature and humidity conditions before mechanical testing.

Manufacturer minimum handling times should not automatically be treated as full cure.

B-72 formulations require additional attention because retained solvent can alter thermoplastic behavior. Intervention layers should be allowed to dry fully before secondary adhesive is introduced.

A defined mass-loss or extended drying criterion may ultimately provide a more defensible procedure than simply waiting a fixed number of hours.

Curing and drying history should be recorded as an experimental variable because it may influence results significantly.

22.13. Tier 2 — Tablet-Fracture Simulation

Tier 2 should move from generic adhesive specimens to a geometry designed to reproduce the structural behavior of a broken tablet.

The specimen should be a relatively thin rectangular marble beam or plate containing a controlled transverse fracture.

After repair, the specimen would be subjected to flexural loading so that the bonded fracture experiences the combination of tension and compression characteristic of bending.

The objective is not to replicate one exact headstone dimension at reduced scale.

It is to create a repeatable test in which the repaired fracture performs the same **structural function** as a tablet repair.

An intact unfractured specimen group should establish the baseline flexural behavior of the marble itself.

22.14. Tablet Test Groups

The highest-value Tier 2 comparisons would include:

Akepox 5010 direct bond

Paraloid B-72 structural bond

B-72 intervention layer + AKEPOX 5010

Tenax Domo 10

Polyester comparator

and, where the joint geometry legitimately permits,

IG10

HXTAL could serve as an additional conservation-epoxy reference.

The principal outcome should not be which repaired specimen approaches intact-marble strength most closely.

The principal outcome should be the combination of service capacity, stiffness, displacement, fracture path, and stone loss.

22.15. Creating Reproducible Fractures

Perfectly reproducible natural fractures are difficult to create because crack paths follow mineral fabric.

Saw-cut joints are easier to standardize but do not reproduce true fracture topography.

A hybrid approach may therefore be appropriate.

Specimens could be lightly notched in a defined location and fractured mechanically so the break initiates predictably while remaining a genuine irregular marble fracture.

The pieces would then be returned to their original orientation for repair.

Such a method should be developed with materials-testing expertise to avoid introducing an artificial crack geometry that overwhelms the adhesive variable.

22.16. Tier 3 — Multi-Piece Monument Mock-Ups

Tier 3 should directly evaluate the central limited-bond hypothesis.

Scaled marble or equivalent calcitic-stone blocks would represent a monument die resting upon a base.

The test should reproduce a broad horizontal interface with dead load, bearing, friction, and supplemental restraint.

Candidate systems should include:

System A — Continuous structural epoxy bond

System B — Localized Pratley pads without controlled bearing

System C — Stable bearing + lead + localized Pratley + maintainable perimeter

System C2 — Stable bearing + lead + B-72 intervention layer + localized Pratley

System D — Mechanical dowel reinforcement + bedding/joint material

System E — Bearing/mineral-setting system without structural adhesive

Not every experiment must include every group, but these represent the principal treatment philosophies that the paper seeks to compare.

22.17. Full-Scale Versus Scaled Mock-Ups

Small mock-ups reduce material cost and allow larger sample populations. Their disadvantage is that adhesive area, monument mass, leverage, and contact mechanics do not necessarily scale linearly.

A staged approach is preferable. Initial system comparisons can use scaled specimens to identify gross differences. The most promising and consequential systems should then be reproduced at larger scale using dimensions and weights more representative of actual cemetery components. One or more full-scale sacrificial mock monuments could provide particularly valuable confirmation before conclusions are converted into field guidance. The purpose is not to prove that every monument behaves like the mock-up. It is to determine whether the limited-bond mechanism behaves as predicted when mass, friction, and overturning leverage become realistically significant.

22.18. Shear Testing of Multi-Piece Systems

One Tier 3 loading mode should apply progressively increasing horizontal force while maintaining realistic vertical dead load.

The test would measure the force required to initiate movement, the displacement that occurs before significant joint damage, and the sequence by which friction, perimeter material, adhesive, or reinforcement becomes engaged.

This would help answer whether localized adhesive materially increases resistance beyond gravity and friction and how that resistance compares with full-surface bonding or dowels.

Instrumentation should record displacement continuously. The first measurable slip may be more useful for serviceability than the final catastrophic load.

22.19. Overturning or Eccentric Loading

A second Tier 3 test should reproduce progressive rocking or overturning.

Force applied at a known height above the joint would create an increasing moment.

The test would record when one edge begins to unload or lift, when adhesive restraint becomes active, where cracking initiates, and the eventual failure mode.

This geometry is particularly important because full-area adhesive, localized pads, and mechanical pins are expected to diverge more dramatically under uplift than under pure compression.

The outcome should include both load and resulting damage. A system surviving the greatest overturning moment while destroying a large portion of the base may not represent the preferred conservation outcome for a low monument.

22.20. Bearing as a Controlled Variable

The Gravestone Guardians hypothesis depends upon stable bearing, so bearing quality must be controlled experimentally.

One comparison series should use properly distributed bearing.

A deliberately deficient-bearing group may also be informative because it could demonstrate what happens when adhesive is inadvertently required to compensate for poor support.

This comparison would provide empirical support for one of the paper's recurring claims: **adhesive cannot be evaluated independently of the support system beneath it.** Such data could be extremely useful in preservation training.

22.21. Pad Area as an Experimental Variable

Within the limited-bond groups, adhesive area should vary systematically.

For example, specimens could use low, medium, and comparatively high percentages of the available interface area while keeping pad placement and material consistent.

The objective would be to determine how increasing bonded area affects initial movement, ultimate capacity, stiffness, failure location, and stone loss.

The result should not be converted automatically into a universal recommended percentage. It would instead establish whether the proposed relationship actually exists and where diminishing returns may begin. If increasing adhesive area substantially raises stone-loss severity while adding little meaningful service capacity, that would strongly support limited bonding. If low-area systems repeatedly release under modest loads, the method would require revision. Either outcome would improve practice.

22.22. Pad Location as an Experimental Variable

A smaller study should examine pad placement.

Interior pads can be compared with pads positioned near edges under eccentric loading.

The expectation is that edge-adjacent bonds may produce greater peel stresses and higher risk of breakout, particularly in weathered specimens.

Confirmation would support the field guidance proposed in Chapter 20. If the difference proves negligible within realistic geometries, pad placement criteria could be simplified. Again, the purpose is to test existing assumptions rather than codify them without evidence.

22.23. Tier 4 — Aging Before Mechanical Testing

The most informative adhesive groups from Tiers 1–3 should be reproduced and environmentally aged before mechanical testing.

A matched unaged group would serve as the baseline. Comparison should focus not only on percentage strength retained but on whether the **failure mode changes after aging**. An adhesive joint could lose only modest ultimate strength yet become substantially more damaging if aging causes the fracture to migrate into the marble. Likewise, an aged joint might become weaker while failing more cleanly at the treatment interface. Both changes matter.

22.24. Retreatability Experiments

After mechanical and environmental testing, separate specimens should be dismantled intentionally.

For direct epoxy joints, the procedure should document what mechanical intervention is required.

For B-72 joints, appropriate solvent-assisted techniques should be evaluated.

For intervention-layer systems, the study should determine whether solvent can actually reach and weaken the interface after the secondary adhesive and environmental aging are present.

For localized Pratley systems, the study should determine whether unbonded portions of the interface materially improve access and mechanical separation.

The resulting data should include treatment time, tools or solvents required, residue remaining, stone loss, and whether the original surfaces remain suitable for future repair.

This may prove more valuable to conservation practice than another table of maximum tensile strength.

22.25. Field Exposure Program

Laboratory aging should be accompanied by long-term outdoor exposure.

Replicate nonhistoric marble specimens containing selected joints could be mounted at one or more secure exterior test locations and documented periodically.

A New England exposure site would be especially relevant to Gravestone Guardians because it would incorporate actual precipitation, freeze-thaw cycling, summer heating, biological colonization, humidity, and seasonal variation.

Specimens should be positioned to reproduce both exposed vertical fracture lines and protected horizontal interfaces.

Annual or semiannual observations could document discoloration, cracking, joint movement, biological growth, moisture patterns, and visible deterioration.

Some specimens could be destructively tested at scheduled intervals while others remain in long-term exposure. This field program would not produce rapid answers. It would create a growing dataset capable of testing whether laboratory acceleration predicts real performance.

22.26. Data Transparency

Experimental credibility depends upon documenting unsuccessful as well as successful results. Specimen dimensions, materials, batch numbers, mixing procedures, cure conditions, weathering protocols, failures, excluded specimens, raw loads, and damage observations should be retained. Photographs of every failed surface would be especially valuable. Where possible, numerical data should ultimately be published alongside the technical paper or retained in a Gravestone Guardians research archive.

A transparent dataset would allow other conservators and researchers to challenge the interpretation, reproduce selected tests, or compare future adhesives against the same baseline. That would move the work beyond internal product validation toward useful conservation research.

22.27. Collaboration

Several portions of the proposed program exceed what should reasonably be attempted as informal field experimentation. Universal testing machines, controlled environmental chambers, ultrasonic instrumentation, fracture analysis, statistical design, and reliable accelerated-aging protocols benefit from collaboration with a materials-science, civil-engineering, conservation-science, geology, or historic-preservation laboratory.

Gravestone Guardians can contribute the practical monument-setting questions, field geometry, materials, treatment systems, weathered-stone observations, and long-term cemetery monitoring. A laboratory partner can contribute test design, instrumentation,

reproducibility, and statistical analysis. The strongest study would combine both forms of expertise. Getty's grout project provides a useful precedent: conservation problems were approached through interdisciplinary evaluation rather than forcing existing construction-material standards unchanged onto heritage materials. That model is particularly appropriate here.

23. Evaluating Failure Rather Than Maximum Strength

23.1. The Highest Number Is Not the Conservation Answer

Traditional structural testing naturally produces a maximum load. The specimen is stressed until it breaks, and the resulting number becomes an easily compared measure of performance. For historic marble conservation, that number is necessary but insufficient.

Consider two repaired specimens. Specimen A carries 5,000 units of load before failing by tearing a large section from the marble. Specimen B carries 3,500 units before separating principally within a replaceable treatment interface and leaving the historic substrate nearly intact. If expected service demand is only 1,000 units, both systems possess substantial capacity. The additional 1,500 units carried by Specimen A may represent useful reserve capacity. It may also represent **excess capacity purchased with original stone**. Without considering the required service load and damage produced at failure, maximum strength alone cannot determine which repair is preferable.

23.2. Three Separate Questions

Experimental interpretation should therefore distinguish three questions.

Was the repair strong enough?

This is the service-capacity question.

How did the repair behave before failure?

This is the stiffness, displacement, creep, and serviceability question.

What was damaged when the system finally failed?

This is the conservation-consequence question.

A repair system should not be judged until all three are answered.

23.3. Service Capacity

Service capacity should be defined in relation to the structural role of the repair. For a tablet fracture, sufficient capacity means that the repaired tablet can tolerate reasonably foreseeable bending and handling without joint failure. For a low multi-piece monument, sufficient capacity means that the component remains stable against ordinary sliding, rocking, and environmental disturbance. For a tall or safety-critical component, the required capacity may be considerably greater. The experimental program should not attempt to create one universal minimum strength for all monuments. Instead, it should

compare treatments within defined representative structural scenarios. This allows excess capacity to be recognized rather than automatically rewarded.

23.4. Reserve Capacity

No conservation repair should be designed to fail at the first slight exceedance of expected normal load. Some reserve is necessary because actual cemetery conditions contain uncertainty. Wind, impact, vandalism, ground movement, handling, falling branches, and maintenance activities cannot be predicted exactly.

The debate is therefore not between “strong repair” and “weak repair.” It is between **adequate reserve capacity** and **unnecessary excess capacity that materially worsens the failure hierarchy**. The experimental program should seek evidence of the point at which additional adhesive area, pin stiffness, or bond strength no longer provides proportionate preservation benefit.

23.5. First Movement Versus Ultimate Failure

For multi-piece monument systems, the force producing first measurable movement may be as important as the force producing catastrophic failure.

A component that begins sliding under modest load but does not fully detach until a much higher load has inadequate serviceability even though its ultimate capacity appears impressive.

Conversely, a system might remain completely stationary through a substantial service range and then release relatively cleanly at a predictable overload. That behavior could be conservation-favorable.

The test record should therefore distinguish:

- onset of movement;
- opening of the joint;
- permanent residual displacement;
- initiation of visible cracking;
- peak load; and
- final separation or collapse.

This produces a much richer description than one ultimate load value.

23.6. Stiffness as an Outcome

Load-versus-displacement curves can reveal how the repair responds before it breaks. A highly rigid system may show very little movement until sudden fracture. A more compliant system may accommodate modest displacement while continuing to carry load. Neither behavior is inherently preferable. Excessive compliance can allow visible instability, while excessive rigidity can concentrate stress in brittle historic stone. The desired range depends upon monument type. Recording stiffness allows the researcher to determine whether treatments that achieve similar ultimate capacity reach that capacity through dramatically different mechanical behavior. This is especially important when comparing full epoxy bonding, localized putty, thermoplastic acrylics, mineral materials, and mechanical pins.

23.7. Failure Location

Every tested specimen should receive a standardized failure-location classification.

At minimum, categories should distinguish:

adhesive interface failure

cohesive adhesive failure

mixed adhesive/cohesive failure

superficial cohesive marble failure

deep cohesive marble failure

secondary crack propagation

edge breakout

reinforcement-related breakout

and

bearing-related failure

A single specimen may exhibit more than one category.

The proportions of the fracture surface associated with each mechanism could be estimated photographically where practical.

This would provide substantially more information than simply recording “substrate failure.”

23.8. Stone-Loss Area

The surface area of historic marble removed during failure should be measured.

Digital photographs taken perpendicular to the failed surface with a scale reference can allow image analysis to estimate the area of adhesive residue and stone loss. This is particularly useful for comparing localized adhesive pads.

A pad occupying 10 cm^2 that removes a 25 cm^2 spall has produced damage beyond its original bonded footprint.

Another system whose damage remains substantially within the original bonded area would present a more favorable failure geometry even if both are technically cohesive marble failures.

The ratio between damaged area and original bonded area could therefore become a useful comparative metric.

23.9. Stone-Loss Depth and Volume

Area alone cannot distinguish a superficial grain loss from deep breakout. Depth should therefore be estimated or measured. Simple mechanical depth gauges may be sufficient for large losses. Three-dimensional photogrammetry or surface scanning could provide much better volumetric comparison where equipment is available.

Stone-loss volume may ultimately be one of the most intuitive conservation outcomes:

How much original marble was sacrificed when the repair failed? A system producing half the ultimate strength but one-tenth the original-material loss may be highly attractive if both exceed the service requirement comfortably.

23.10. Crack Propagation Distance

New cracking should also be quantified.

The maximum distance a crack travels beyond the original adhesive footprint can provide a useful measure of stress transfer into untreated stone.

A fracture remaining within or immediately adjacent to the bonded area differs from a crack crossing a large portion of the specimen.

Crack length alone will not capture every consequence, but it is especially useful in tablet simulations where new fracture migration represents one of the primary concerns surrounding rigid epoxy joints.

23.11. Damage to Historic Surface or Detail

Laboratory specimens do not contain inscriptions or carvings, but real monuments do. The research scoring system should therefore distinguish generic stone volume from **high-value surface loss** when it is later applied to field case studies. Loss of several cubic centimeters from an uncarved concealed bearing surface is not conservation-equivalent to the same volume removed from a date, epitaph, portrait relief, or carved molding. The experimental Conservation Failure Index proposed below cannot fully account for cultural significance in a laboratory coupon. Field treatment selection must add that object-specific value judgment. Quantitative testing supports professional judgment. It does not replace it.

23.12. Retreatability as a Performance Metric

A joint can survive mechanical testing and still perform poorly as a conservation treatment if future separation requires extensive destruction. Retreatability should therefore receive its own score.

Possible variables include:

- time required to separate the specimen;
- whether solvent, heat, cutting, impact, or drilling is required;
- amount of adhesive residue remaining;
- amount of original stone removed during retreatment;
- whether the original joint geometry remains identifiable;
- whether the surfaces remain suitable for another repair.

These variables can be measured after equivalent environmental aging so that an initially soluble system is not credited for reversibility it no longer retains effectively in practice.

23.13. A Conservation Failure Index

To compare systems that differ simultaneously in strength, stone loss, fracture propagation, and retreatability, this paper proposes development of a **Conservation Failure Index (CFI)**.

The CFI should not replace raw experimental measurements. Its purpose would be to summarize the conservation consequence of failure in a form that can be compared among systems after the underlying data have been reported.

The index would be most useful if a **lower score represents less damaging failure** and a higher score represents progressively greater loss and retreatment difficulty. A provisional 0–100 scale could combine several normalized factors:

Table 23.1: Provisional Components and Weights for the Conservation Failure Index

Component	Provisional Weight
Original marble volume lost	30%
Crack propagation beyond repair	20%
Depth/severity of substrate failure	15%
Loss of joint accessibility/retreatability	15%
Residual instability or hazardous release	15%
Visual/staining consequences	5%

Note. These weights are proposed for discussion and would require validation. The table should not be presented as an established conservation standard. Its value lies in forcing the experiment to treat damage severity as a measured outcome rather than an anecdotal observation.

23.14. Why Safety Must Be Included

A damage index focused only on protecting marble could produce perverse conclusions.

Imagine a joint that releases cleanly without removing a single marble grain but allows a heavy upper monument section to fall. Its material-loss score would appear excellent. Its preservation and safety performance would be unacceptable.

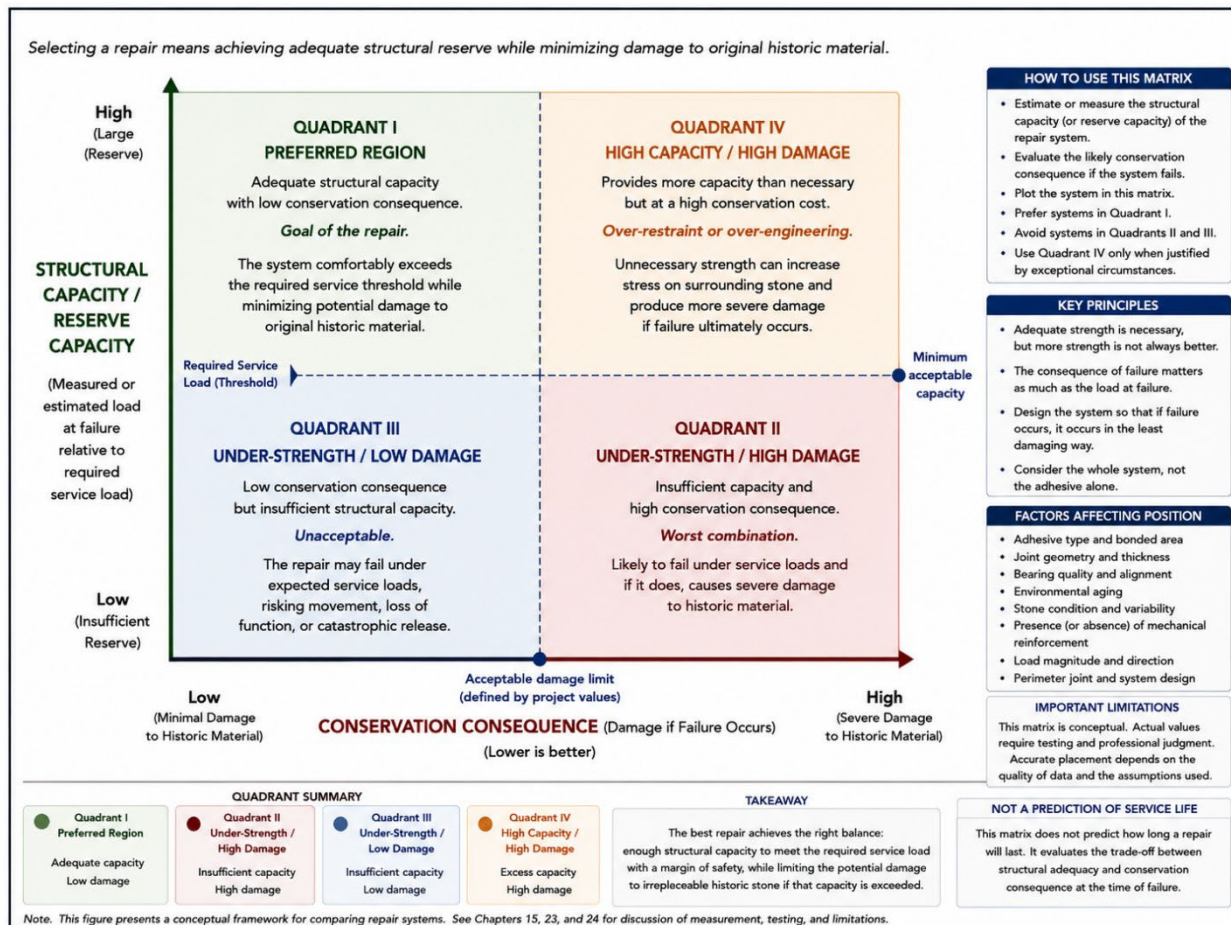
Residual stability or hazardous release must therefore be included in any conservation failure evaluation. This reinforces the principle developed in Chapter 15: the preferred system is not simply the one that fails most gently. It must remain adequately stable until loads exceed the range it is reasonably expected to survive.

23.15. A Two-Axis Interpretation May Be Better Than One Score

A single composite score is convenient but risks hiding important tradeoffs. For final analysis, systems should also be plotted conceptually on two axes: **structural capacity** on one axis and **conservation damage consequence** on the other. The ideal region lies where capacity comfortably exceeds the required service threshold while damage consequence remains low. A very weak, low-damage system would fall below the service threshold. A very strong but highly destructive system would provide unnecessary capacity at a conservation cost. A system with adequate-to-high capacity and modest damage would occupy the preferred region.

Figure 23.1 expresses the central experimental proposition of this paper by plotting structural capacity against conservation consequence rather than treating either variable independently. The preferred repair is not simply the system carrying the greatest load, but one that exceeds its required service threshold while producing comparatively limited damage to original stone if its capacity is ultimately exceeded.

Figure 23.1: Structural Capacity Versus Conservation Consequence



Note. This matrix is conceptual and compares structural capacity with conservation consequence; it does not predict service life. Actual placement requires project-specific testing, evidence, and professional judgment.

23.16. Failure Efficiency

Another potentially useful derived quantity is a **failure efficiency ratio** comparing achieved structural capacity with damage produced. The exact mathematical form should be developed only after pilot data reveals useful measurement ranges. Conceptually, the question is: **How much useful structural capacity was obtained per unit of irreversible historic-material loss?** The concept should not encourage maximizing strength indefinitely. Instead, the service threshold should remain the reference point. Once a

system comfortably exceeds required capacity, improvements in damage behavior become increasingly important.

23.17. Interpreting Cohesive Marble Failure More Carefully

One likely outcome of the proposed testing is that several strong systems will produce cohesive marble failure. That finding should not end the analysis. Researchers should compare whether the fracture is superficial or deep, whether it remains localized, whether it crosses historic-style fracture planes, and how aging changes its character.

Podany's findings established that multiple adhesive families can exceed marble cohesion under controlled conditions. The next useful research step is to differentiate the **severity** of those cohesive failures. The statement “the marble broke first” is scientifically important. It is no longer sufficient by itself.

23.18. Interpreting Adhesive Failure More Carefully

The same caution applies to apparently desirable adhesive failure. A system releasing cleanly at 20 percent of the required service load is not conservative. A system releasing cleanly at three times expected service demand may be exceptionally useful. Failure mode and failure threshold must therefore remain linked. This relationship is the core of the paper's proposed failure hierarchy.

23.19. Aging-Induced Changes in Failure Hierarchy

One of the most valuable experimental outcomes will be determining whether environmental aging changes **where** the repaired system fails. An unaged epoxy joint may fail through the marble. After aging, it may begin debonding at the interface. A B-72 system might initially provide sufficient capacity but creep or weaken at elevated temperature. A mineral grout might initially fracture internally but develop increasing stone adhesion as curing continues. A Pratley pad might retain strength while weathered marble beneath it becomes increasingly substrate-limited. The change in failure hierarchy over time may be more important than the change in maximum load. This should be reported explicitly.

23.20. The Preferred Experimental Outcome

The most desirable repair system will probably not be the strongest one tested. It should instead satisfy several conditions simultaneously. It should remain stable through the defined service range with reasonable reserve capacity. It should avoid excessive movement or creep. Its environmental aging should be limited and predictable. When overloaded, damage should remain as localized and repairable as practical. Its deliberate retreatment should not require disproportionate destruction of original stone. This represents a more demanding definition of adhesive performance than maximum bond strength. It is also more closely aligned with conservation.

24. Environmental Aging Protocol

24.1. Why Aging Must Be Part of Structural Evaluation

A structural adhesive selected for a cemetery monument is not being asked to perform for several weeks. The intended service life is measured in years or decades. During that period, marble and repair materials experience repeated temperature changes, moisture movement, freezing, solar radiation, biological activity, and occasional contaminants. The properties measured immediately after laboratory cure therefore represent only the starting condition. Environmental aging should consequently be built into the primary experimental design rather than added later as an optional durability study. The central comparison is not simply **Material A versus Material B**. It is **Material A and Material B after both have been allowed to experience mechanisms relevant to cemetery exposure**.

24.2. No Single Accelerated Aging Cycle Can Reproduce a Cemetery

Exterior monuments experience multiple interacting environmental processes. Rain changes stone saturation. Solar heating changes temperature gradients and polymer stiffness. Freezing acts differently depending upon water availability. Salts move with moisture. Drying produces crystallization and dimensional change. Biological colonization changes surface wetting. A single laboratory cycle cannot reproduce this complete environment. Attempting to combine every mechanism into one aggressively accelerated protocol can make interpretation more difficult because researchers cannot determine which exposure caused the observed change. A modular aging program is therefore preferable. Separate specimen populations should experience controlled thermal cycling, wet-dry cycling, freeze-thaw exposure, ultraviolet aging, salt exposure where relevant, and sustained mechanical loading. A smaller combined-aging series can then examine interactions among the most important variables.

Because no single accelerated exposure reproduces the cemetery environment, Figure 24.1 organizes the principal aging mechanisms as complementary experimental variables rather than as a single severity scale. Thermal cycling, moisture, freeze-thaw exposure, ultraviolet radiation, salts, sustained loading, and combined aging can thereby be evaluated separately before their interactions are examined.

Figure 24.1: Environmental Aging Test Matrix

Environmental Aging Test Matrix Controlled conditioning variables, measurements, and relevant failure mechanisms for evaluating monument repair systems.				
AGING VARIABLE (Exposure Mechanism)	CONDITIONING VARIABLES (What We Control)	EXAMPLE PROTOCOL / RANGE (Indicates Typical Test Conditions)	MEASUREMENTS (Primary Outcomes)	RELEVANT FAILURE MECHANISMS (What We Are Investigating)
 1. THERMAL CYCLING (Temperature Change)	- Temperature range - Dwell time at each extreme - Ramp rate - Number of cycles	Example: -20 °C to +60 °C Dwell: 1–2 hr Ramp: 1–2 °C/min Cycles: 25, 50, 100, 200	- Joint strength (tension / shear / flexure) - Stiffness (elastic modulus) - Visual / microscopic inspection - Acoustic response (as applicable)	- Differential thermal movement - Residual stresses - Microcracking at interfaces - Loss of bond / cohesion
 2. WET-DRY CYCLING (Moisture Fluctuation)	- Wetting method and duration - Drying method and duration - Water quality - Number of cycles	Example: 24 hr water immersion (20 ± 2 °C) → 24 hr drying (20–30% RH, 20 °C) Cycles: 10, 25, 50, 100	- Joint strength (tension / shear / flexure) - Stiffness (elastic modulus) - Visual / microscopic inspection - Moisture content (as applicable)	- Absorption / desorption stresses - Swelling / shrinkage - Interfacial weakening - Soluble salt movement
 3. FREEZE-THAW CYCLING (Ice Formation)	- Temperature range - Dwell time - Freeze medium (air / water) - Number of cycles	Example: -20 °C to +20 °C Dwell: 2 hr at each extreme Freeze medium: water Cycles: 25, 50, 100, 200	- Joint strength - Stiffness - Visual / microscopic inspection - Mass change (as applicable)	- Ice crystallization pressure - Microcracking in stone - Debonding at interfaces - Loss of cohesion
 4. UV / PHOTO-OXIDATION (Solar Radiation)	- Irradiance / UV intensity - Wavelength range - Exposure temperature - Exposure duration	Example: UVA-340 Irradiance: 0.76 W/m ² @ 340 nm Temp: 60 °C (black panel) Exposure: 250, 500, 1000 hr	- Color change (ΔE) - Surface degradation (microscopy) - Mechanical properties - Chemical change (FTIR, as applicable)	- Polymer degradation - Embrittlement - Yellowing / discoloration - Loss of strength
 5. SALT EXPOSURE (Salt Crystallization)	- Salt type and concentration - Application method - Drying conditions - Number of cycles	Example: 3% NaCl solution 24 hr wetting → 24 hr drying (20–30% RH, 20 °C) Cycles: 10, 25, 50	- Joint strength - Visual / microscopic inspection - Mass change - Ion analysis (as applicable)	- Salt crystallization pressure - Efflorescence / subflorescence - Surface scaling - Interfacial damage
 6. SUSTAINED MECHANICAL LOADING (Creep)	- Load level (% of initial strength) - Mode (compression / tension / shear / flexure) - Environment (dry / wet) - Duration	Example: 25%, 50%, 75% of initial capacity Environment: 20 °C, 50% RH Duration: 30, 60, 90 days	- Displacement / deformation over time - Creep rate - Residual strength after loading - Visual inspection	- Time-dependent deformation - Stress relaxation - Adhesive creep - Interfacial slippage
 7. CYCLIC MECHANICAL LOADING (Fatigue)	- Load range (% of capacity) - Frequency - Waveform - Number of cycles	Example: 10–40% of capacity Frequency: 0.1–1 Hz Cycles: 10 ³ , 10 ⁴ , 10 ⁵ , 10 ⁶	- Stiffness change - Residual strength - Crack initiation (microscopy) - Acoustic / vibration (as applicable)	- Fatigue crack initiation - Crack propagation - Progressive joint degradation - Loss of stiffness
 8. COMBINED EXPOSURE (Multi-Stressor)	- Combination sequence (e.g., T-cycle + wet-dry + UV + salt) - Duration / cycles - Environment	Example: Defined sequence or simultaneous exposure Total duration: as designed (e.g., 100 cycles)	- Joint strength - Visual / microscopic inspection - Mass change / moisture - Chemical change (as applicable)	- Interaction effects - Accelerated degradation - Unexpected failure modes - Cumulative damage
NOTES ON USE This matrix organizes the principal environmental mechanisms that influence repair performance. Selected variables should reflect the intended service environment. Multiple aging variables are complementary; no single test replicates real-world conditions. Results should be interpreted comparatively within each testing program. GENERAL MEASUREMENTS ACROSS ALL TESTS  Dimensional change  Time to failure / endurance  Visual appearance (dulling, staining)  Microstructure (SEM, OM)  Data for Conservation Failure Index (CFI)				
Note: This matrix presents a framework for designing and reporting aging experiments. Specific protocols, values, and measurements should be selected based on research objectives, material characteristics, available facilities, and conservation relevance.				

Note. This matrix organizes conditioning variables, controlled parameters, measurements, and relevant failure mechanisms for experimental design. Protocol values should be selected according to the research objective, material condition, available facilities, and conservation relevance.

24.3. Establishing a Baseline

Before environmental aging, every specimen should undergo nondestructive baseline documentation. Measurements should include dimensions, mass, high-resolution photographs, visible joint width, color where relevant, and ultrasonic velocity of the marble where geometry permits. For system-level specimens, initial stiffness and small non-destructive proof loading may also be useful if it can be performed below any level expected to alter the joint. The same measurements should be repeated after aging. This permits deterioration to be identified before specimens are loaded destructively.

24.4. Thermal Cycling

Thermal cycling should reproduce repeated dimensional change without using temperatures so extreme that the test becomes unrelated to cemetery exposure. Research

on marble demonstrates that thermal cycles can progressively increase microcracking and reduce elastic properties because of the anisotropic thermal behavior of calcite and differences among marble fabrics. The precise temperature range should be established using recorded or published exterior stone temperatures relevant to the intended climate. A broad initial laboratory screening range could reproduce cold winter and strongly sun-heated summer conditions without approaching temperatures used in aggressive geological thermal-damage experiments. Heating and cooling rates should be controlled and recorded. The purpose is repeated realistic strain, not thermal shock for its own sake.

24.5. Why Extremely High Thermal Aging Should Be Avoided Initially

Some marble weathering studies use maximum temperatures around 90°C or higher to accelerate thermally induced degradation and reveal differences among marble fabrics. Such procedures are scientifically valuable for characterizing marble susceptibility. They may be too aggressive for the first stage of an adhesive durability study intended to approximate cemetery exposure. Very high temperature can change polymer behavior, drive additional resin cure, alter B-72 substantially, and generate marble damage beyond typical field conditions. A two-level approach is preferable. A realistic service-temperature cycle should evaluate likely field behavior. A separate severe screening cycle can later establish relative vulnerability and identify mechanisms under accelerated stress. The results should not be conflated.

24.6. Wet-Dry Cycling

Wet-dry cycling is essential because historic exterior marble rarely remains continuously dry. Specimens should undergo controlled wetting followed by drying under reproducible temperature, humidity, and airflow. The method should avoid saturating specimens in a manner grossly unlike the actual joint exposure unless full saturation is being tested intentionally. Capillary wetting may provide a particularly relevant condition for some specimen geometries because it allows water to enter through the stone rather than being applied directly into an otherwise sealed repair. Measurements of mass before and after cycling can help identify changes in absorption and drying. Visual observations should record whether moisture persists preferentially around adhesive zones.

24.7. Moisture Transport Around Bonded Areas

One objective of wet-dry testing should be determining whether different bonded areas change local water distribution. A continuous epoxy layer, localized Pratley pads, B-72 intervention layer, mineral grout, and unbonded mineral interface may behave differently. The experiment need not provide a complete pore-scale moisture model to be informative. Simple comparative measurements—capillary uptake, drying mass curves, infrared

surface observations where available, visible wetting patterns, and salt deposition location—could identify major differences. This is particularly important for intervention-layer systems because polymer barriers can improve retreatability while also affecting water movement through stone.

24.8. Freeze-Thaw Cycling

Freeze-thaw exposure should be included for treatments intended for cold climates. The protocol must be designed carefully. ASTM's current work toward a natural-stone-specific freeze-thaw method explicitly recognizes that ASTM C666 was developed for concrete and does not fully address the testing requirements of dimension stone. Natural-stone methods such as EN 12371 provide useful reference frameworks, and published heritage-stone studies frequently use controlled freeze-thaw exposure followed by physical and mechanical measurements. For the present research, the most important requirement is transparent reporting of specimen saturation, freezing temperature, thaw temperature, dwell periods, number of cycles, and specimen condition. The test should be described as a defined experimental protocol rather than as an exact simulation of a specified number of natural winters.

24.9. Moisture State Before Freezing

Freeze-thaw results are strongly dependent upon specimen moisture condition. Dry marble contains little free water available for ice formation. Fully saturated marble represents a much more severe condition. Actual cemetery stone cycles through intermediate saturation states. The experimental program should therefore define moisture conditioning explicitly. One approach would compare a moderate controlled saturation condition with a more severe high-saturation screening condition. Such testing could reveal whether a repair system performs adequately during ordinary exposure but becomes vulnerable under unusually wet conditions such as flooding or chronic drainage failure. This distinction is more useful than one undefined “freeze-thaw” category.

24.10. Freeze-Thaw Measurements

Specimens should be examined periodically rather than only at the end of the cycling program. Observations should include mass change, visible cracking, joint opening, adhesive discoloration, spalling, and ultrasonic velocity where practical. Changes in ultrasonic velocity are particularly useful because marble weathering research demonstrates sensitivity to microcrack development before catastrophic fracture becomes visible. Mechanical testing after the complete aging sequence can then establish whether nondestructive indicators correlate with actual loss of joint capacity.

24.11. UV and Photo-Oxidative Exposure

UV exposure is most relevant to adhesive exposed at or very near the monument surface.

Concealed Pratley pads or epoxy deep inside a horizontal joint receive far less direct irradiation than a visible tablet bond line.

Specimen design should therefore reproduce realistic exposure rather than irradiating every adhesive surface equally.

Published research on conservation polymers used on outdoor stone has deliberately subjected B-72 and other polymers applied to marble to photo-oxidative weathering while evaluating chemical and visual changes.

Comparable testing can help distinguish adhesives that retain mechanical performance but discolor significantly from those maintaining both structural and aesthetic stability.

24.12. Color Measurement

Because white marble is highly sensitive aesthetically to discoloration, color should be measured instrumentally where possible.

CIE Lab* measurements taken before and after aging can quantify yellowing or darkening that photographs alone may not reproduce reliably.

Measurements should focus both on the visible adhesive and the marble immediately adjacent to the joint.

A resin that remains visually clear but creates a dark penetration halo in the stone presents a different problem from one whose exposed polymer itself yellows.

Aesthetic aging should therefore be separated into **resin color change** and **substrate color change**.

24.13. Salt Exposure

Salt crystallization testing should be included selectively rather than applied automatically to every adhesive specimen. Salt contamination varies greatly among cemeteries, and severe standardized sodium-sulfate cycling can represent an extreme exposure.

EN 12370-derived protocols are commonly used for natural stone, but researchers have modified the standard because high salt concentrations and drying temperatures can overstate some real-world conditions.

A conservation-oriented study could therefore use two levels. A moderate low-concentration exposure could examine whether adhesive zones redirect salt deposition under more realistic conditions. A severe screening protocol could identify systems particularly vulnerable to salt crystallization. These results should remain distinct.

24.14. Why Sodium Sulfate Is Useful but Imperfect

Sodium sulfate is commonly used in accelerated stone durability testing because phase changes and crystallization can generate severe pore stress. It is not the only salt encountered in cemeteries.

Chlorides, nitrates, carbonates, sulfates, and mixtures can arise from soil, pollution, fertilizers, biological activity, deicing salts, historic mortars, or cleaners. Testing every possible salt mixture would be impractical. Sodium sulfate can therefore function as a standardized comparative stressor without being described as a universal model of cemetery chemistry. Field monitoring should complement the laboratory work by documenting actual salt conditions where they occur.

24.15. Sustained Mechanical Loading

Environmental aging should include specimens maintained under continuous mechanical demand. For multi-piece mock-ups, a realistic compressive dead load should remain in place throughout portions of thermal and moisture cycling. Selected adhesive joints should also experience sustained shear or eccentric load below their short-term failure capacity. This is particularly important for thermoplastic adhesives, putties serving as unintended bearing material, and lead-supported assemblies. Displacement should be monitored over time. A system remaining intact but gradually changing alignment may exhibit unacceptable creep even though it never experiences sudden adhesive failure.

24.16. Cyclic Mechanical Loading

Some monument movements are repetitive rather than sustained. Low-amplitude lateral cycling can simulate wind, minor rocking, or repeated small environmental movements. The objective should not be to reproduce millions of engineering fatigue cycles at arbitrary high frequency. Moderate cyclic loading before and after environmental aging can reveal whether repeated movement progressively damages an interface whose monotonic strength remains high. This may be particularly useful for comparing rigid full-area epoxy bonds with limited adhesive systems. The latter may permit small movements differently because large portions of the interface remain governed by bearing and friction.

24.17. Combined Aging

After individual mechanisms have been evaluated, selected systems should undergo combined cycles. One practical sequence could include wetting, freezing, thawing, drying, and moderate thermal heating in repeated blocks. A UV component may be added for specimens containing exposed adhesive. The combined test should be designed after individual exposures identify the most relevant vulnerabilities. This staged process helps avoid an uninterpretable “torture test” in which every specimen fails but the reason remains unknown.

24.18. Number of Aging Cycles

No universal number of cycles can be justified in advance as representing a certain cemetery service life. Pilot testing should determine a range sufficient to produce measurable change without destroying every specimen. Multiple withdrawal points are preferable to a single endpoint. For example, matched specimens could be removed after low, intermediate, and high numbers of cycles and tested mechanically. This would reveal the rate at which performance changes rather than merely comparing “before” and “after.” The exact cycle counts should be defined through pilot observations and laboratory capacity.

24.19. Controls

Every aging series requires controls. Unaged bonded specimens establish initial performance. Unbonded marble specimens subjected to the same environmental exposure reveal how much deterioration arises from the stone itself rather than the adhesive. Intact unfractured specimens provide another baseline for the natural loss of marble mechanical properties during aging. Where intervention layers are used, B-72-only specimens help separate behavior of the acrylic layer from the overlying thermoset. Without such controls, deterioration of the repaired specimen cannot be assigned confidently to the repair system.

24.20. Nondestructive Monitoring During Aging

The experimental program should exploit nondestructive measurements whenever practical. Ultrasonic P-wave velocity is particularly attractive for marble because extensive research links declining velocity with increasing microcracking and weathering. Mass change can indicate water uptake or material loss. High-resolution photography can document progressive cracking and discoloration. Joint-width gauges or displacement transducers can identify creep. Colorimetry can quantify yellowing. These measurements create a history of deterioration rather than a single destructive endpoint.

24.21. Post-Aging Mechanical Testing

After environmental conditioning, specimens should be tested using the same mechanical procedures as matched unaged controls. Results should report both absolute capacity and percentage retention. More importantly, failure surfaces should be evaluated according to Chapter 23. An adhesive retaining 90 percent of initial strength but changing from adhesive failure to deep marble fracture may have aged unfavorably from a conservation perspective. Another system retaining only 70 percent but remaining comfortably above service demand and failing with minimal stone loss may present a better long-term treatment hierarchy. Strength retention and damage consequence must be interpreted together.

24.22. Post-Aging Retreatability

Retreatability should also be tested **after** environmental aging. This is essential. A B-72 intervention layer that separates readily after 30 days in the laboratory but becomes difficult to access after years of simulated moisture and thermal cycling may provide less long-term benefit than expected. A localized Pratley system may become more or less mechanically accessible as perimeter materials age. Mineral grouts may continue curing and become harder to remove. Epoxies may embrittle or remain extremely tenacious. These changes affect future conservation directly.

24.23. Outdoor Correlation Specimens

For each major laboratory aging group, matching specimens should ideally remain outdoors under natural exposure. Their progress can be compared periodically with accelerated specimens. If laboratory cycling produces damage mechanisms never observed outdoors, the protocol may require revision. If similar discoloration, cracking, moisture patterns, or stiffness changes occur at different rates, confidence in the acceleration method increases. This iterative relationship between laboratory and field exposure is preferable to assuming in advance that a chamber cycle reproduces nature faithfully.

24.24. New England as a Relevant Exposure Environment

For Gravestone Guardians, a New England field station would provide particularly useful environmental relevance. The region exposes marble to freezing winters, warm summers, rainfall, snow, seasonal humidity, biological colonization, and frequent freeze-thaw transitions. Such a site would not represent every cemetery climate. It would represent the environment in which a substantial portion of GG's field work is performed and therefore provide direct operational value. A second exposure site in a warmer or more moisture-

dominant climate would strengthen generalization if future partnerships make one available.

24.25. Environmental Aging as Part of the Failure Hierarchy

The purpose of environmental aging is ultimately not to produce visually weathered specimens. It is to determine whether the intended failure hierarchy survives time. A limited-bond system may initially provide ideal service capacity and localized failure. After aging, the marble beneath the adhesive may weaken until the same pads remove deeper stone. A B-72 intervention layer may initially provide both strength and retreatability but soften or creep under repeated heating. A mineral grout may initially appear comparatively weak but continue hydraulic curing and become substantially stiffer. A full epoxy bond may retain enormous strength while the surrounding marble progressively loses cohesion. These changes cannot be predicted confidently from initial material data alone.

24.26. Criteria for Successful Aging Performance

A successful system should satisfy several conditions after environmental exposure.

It should retain sufficient capacity for its intended service role.

Permanent deformation should remain limited.

No major new moisture concentration, staining, or uncontrolled substrate deterioration should develop around the treatment.

Failure should remain localized enough to avoid disproportionate historic-material loss.

Where retreatability is an intended advantage, that advantage should remain practical after aging.

These criteria provide a more useful definition of durability than simply requiring the adhesive to remain bonded.

24.27. The Research Standard Proposed by Technical Paper No. 3

The experimental approach developed through Chapters 21–24 establishes a higher evidentiary standard for future Gravestone Guardians material recommendations. A product should not be adopted because a manufacturer reports the highest strength. It should not be rejected because a traditional conservation principle labels it “too strong.” A mineral product should not be assumed compatible because it contains no polymer. A thermoplastic should not be assumed safe because it is soluble. A limited-bond method should not be assumed conservative because it uses less adhesive. Each proposition should instead be tested through comparable substrate conditions, controlled joint

geometry, realistic structural loading, environmental aging, documented failure analysis, and actual retreatability assessment. The desired endpoint is not a monument repair that never fails. No repair can guarantee that outcome. The desired endpoint is a treatment whose **capacity is sufficient, aging is predictable, intervention is proportionate, and eventual failure or retreatment preserves as much original historic marble as reasonably possible**. That is the experimental standard necessary to determine whether the middle ground proposed throughout this paper is merely intuitive—or genuinely better conservation.

25. Reversibility, Retreatability, and Permanence

25.1. Reversibility as a Conservation Ideal

Few concepts have influenced modern conservation practice as strongly as reversibility. The underlying principle is compelling: treatments applied to cultural property should, where practical, be capable of removal without unacceptable alteration of the original material. A future conservator should not be forced to sacrifice historic fabric merely because an earlier practitioner selected a material that could neither be removed nor worked around.

This principle has particular resonance in adhesive repair. A broken marble monument may survive for centuries, while the service life of an adhesive, grout, mortar, pin, or setting material is necessarily finite. Even a material that remains chemically stable may eventually need to be removed because the monument has shifted, the foundation has changed, another fracture has developed, or future conservation knowledge favors a different treatment.

Reversibility therefore represents more than a preference for particular materials. It reflects humility about the permanence of present-day conservation decisions.

The difficulty arises when reversibility is treated as a binary property. Under that simplified interpretation, a soluble acrylic such as Paraloid B-72 is reversible, while a cross-linked epoxy such as Akepox 5010 is irreversible. The distinction is chemically meaningful but does not fully describe the treatment that remains after the adhesive has been placed between pieces of historic marble.

Barbara Appelbaum's influential examination of the reversibility principle addressed this problem directly. She argued that reversibility exists in degrees and that even irreversible treatments should be evaluated according to whether they permit future treatment or retreatability (Appelbaum, 1987). That distinction is particularly useful for exterior stone conservation.

25.2. Material Reversibility and Treatment Reversibility Are Different

A material can remain soluble while the completed treatment is extraordinarily difficult to reverse.

Consider a concentrated B-72 adhesive occupying a deep irregular fracture between two heavy marble components. The polymer may remain soluble in acetone or another appropriate solvent. Yet a future practitioner must still deliver that solvent throughout the bond, allow sufficient contact time for the polymer to soften, manage evaporation and

worker exposure, and physically separate the stone without damaging fragile fracture edges.

If the resin has penetrated microcracks or porous weathered zones, some material may remain below the accessible surface even after the principal joint has been opened. The polymer is chemically reversible.

The **treatment** is reversible only to a degree.

The opposite situation is also possible. Several small pads of an irreversible epoxy putty may occupy a broad horizontal interface whose remaining surface is unbonded. The putty cannot be dissolved after cure, yet a future practitioner may be able to remove the perimeter joint, insert lifting equipment or separation tools through the unbonded interface, lift the component, and address the few adhesive residues individually. The polymer is chemically irreversible.

The assembly may nevertheless be reasonably retreatable. This distinction is one of the most important conclusions developed throughout Technical Paper No. 3.

25.3. Chemical Reversibility

Chemical reversibility refers primarily to the ability to dissolve, soften, swell, depolymerize, or otherwise alter a treatment material sufficiently to permit removal.

Thermoplastic acrylics such as B-72 offer an obvious advantage because the polymer does not become permanently cross-linked during drying. Appropriate solvent can therefore restore enough molecular mobility to soften or dissolve the material.

Thermosetting epoxies behave differently. Akepox 5010, for example, undergoes chemical cross-linking during cure. AKEMI states that once hardened, the product can no longer be removed with solvents; removal requires mechanical methods or temperatures above approximately 200°C, a temperature that would not constitute a realistic conservation removal technique for historic marble (AKEMI GmbH, 2022; see Appendix J, Section J.2).

Pratley Standard Setting Putty likewise cures into a hard, abrasion-resistant material that can subsequently be drilled, filed, or machined. Its manufacturer does not present cured solvent removal as a treatment option (Pratley, 2023; see Appendix J, Section J.8). These materials should therefore be described honestly as chemically irreversible in normal cemetery conservation practice.

Acknowledging that permanence does not automatically prohibit their use. It establishes the conservation cost that must be justified.

25.4. Mechanical Retreatability

Mechanical retreatability describes the ability to gain access to, weaken, cut, separate, or remove a treatment physically without disproportionate loss of original material. Geometry is critical.

A thin epoxy fracture bond passing completely through a two-inch tablet may be chemically permanent and mechanically difficult to remove because the cured resin follows an irregular three-dimensional break. Attempting to cut through it would probably remove some historic marble.

A large die bonded continuously to a base presents an even more difficult condition because nearly the entire interface is inaccessible except from its outer edge.

Several isolated putty pads create a different opportunity. Much of the interface remains open once the perimeter material is removed, potentially allowing the setter to work progressively toward the bonded areas.

Pins introduce another geometry. A stainless-steel dowel secured deeply inside marble with epoxy may be extremely difficult to remove even though the volume of polymer is comparatively small. Cutting the pin can leave permanent metal and adhesive inside the stone; drilling the assembly out enlarges the original intervention.

Retreatability therefore cannot be ranked by the quantity of adhesive alone. The location and accessibility of that adhesive matter just as much.

25.5. Retreatability Through System Design

The system-level sacrificiability developed in Chapter 3 can now be extended into a related principle: **retreatability can be designed**.

A repair becomes more retreatable when permanent interventions are localized, documented, accessible, and separated from replaceable materials.

In the GG limited-bond model, the perimeter setting compound constitutes one accessible layer. Lead wedges constitute another. Localized Pratley pads form the permanent restraint layer. The historic stone remains unbonded across much of the interface.

Such an assembly does not become reversible in the strict chemical sense. It does, however, preserve more physical pathways for future intervention than a full-surface epoxy bond.

Likewise, a B-72 intervention layer beneath permanent adhesive attempts to create retreatability chemically by placing a soluble polymer between the historic stone and the irreversible adhesive.

These two strategies—geometric retreatability and chemical retreatability—need not be mutually exclusive. The possibility of combining them is one of the more promising research directions identified in this paper.

25.6. Reversibility Must Include Damage From Reversal

A treatment should not be credited as reversible merely because a procedure exists for removing it. The consequences of the removal procedure matter.

Large quantities of solvent can affect adjacent coatings, fills, inscriptions, paints, biological patina, or previous treatments. Solvent may mobilize staining compounds into porous stone. Mechanical removal can scratch, chip, abrade, or fracture historic surfaces.

Even attempts to chemically weaken supposedly permanent resins can produce unexpected effects. Previous conservation research has demonstrated that some epoxy and polyester formulations can swell considerably during solvent exposure. Within confined stone joints or drilled holes, such swelling could generate pressure against surrounding material rather than simply releasing the adhesive.

This leads to a more precise conservation question:

Can the treatment be removed or altered later with less damage than would have occurred had a different treatment been selected? That is a considerably higher standard than merely asking whether the adhesive appears on a solvent-solubility chart.

25.7. The Impossibility of Returning the Monument to an Untreated State

Some degree of irreversible change is unavoidable in many structural repairs.

A broken tablet that is lifted, cleaned, realigned, bonded, and reset cannot literally be returned to the condition that existed before treatment. Loose grains may have been lost before arrival. Surfaces will have been handled. Previous adhesive may have been removed. The fracture may contain microscopic resin penetration.

A drilled monument cannot recover the marble removed from the drill hole. A consolidated stone remains altered even if excess consolidant is later removed.

A grout introduced into a deep internal void may never be recoverable completely. Recognizing this reality does not diminish conservation ethics.

It replaces an impossible requirement for perfect reversibility with a more useful obligation to **minimize unnecessary irreversible change and preserve reasonable future treatment options**.

Current AIC guidance emphasizes precisely this broader responsibility. Conservation practitioners are expected to choose methods and materials that support future examination, investigation, treatment, function, access, and physical integrity, while maintaining thorough documentation of examination and intervention (American Institute for Conservation, n.d.).

25.8. Permanence Exists in Degrees of Consequence

The word *permanent* can itself obscure important distinctions.

A permanent epoxy line occupying an existing fracture is different from epoxy deliberately spread several inches beyond the fracture.

A permanent adhesive pad occupying two square inches of a concealed bearing surface differs from a full-area epoxy laminate covering several hundred square inches.

A permanent pin hole through sound interior marble differs from several oversized holes drilled close to weathered edges. All are irreversible interventions.

Their **conservation footprints** are not equivalent.

The amount, location, geometry, accessibility, and cultural significance of the altered material should therefore form part of the treatment decision.

This supports a principle already emerging throughout the paper:

Where permanence is necessary, localize it.

25.9. Reversibility and Structural Safety

A structural treatment cannot be made so easily reversible that it becomes unsafe.

This limitation deserves particular emphasis because reversibility is sometimes discussed independently of the load the repair must carry.

A large elevated fragment cannot be attached using an intentionally weak adhesive merely because future removal would be easier. If predictable service loads can cause release, the treatment threatens the object and potentially the public.

A tall monument section requiring positive mechanical anchorage should not be deliberately under-reinforced in pursuit of theoretical reversibility. The conservation challenge is therefore not to maximize reversibility independently.

It is to maximize retreatability **within the range of treatments capable of providing adequate structural performance.**

Where a highly retreatable system satisfies that requirement, it should generally be favored. Where it does not, greater permanence may be justified.

25.10. Documentation as a Substitute for Some Lost Reversibility

Documentation cannot reverse epoxy or restore a drilled hole. It can, however, preserve information that substantially reduces the damage required during future retreatment.

A future conservator who knows that four Pratley pads were positioned five inches inward from the monument corners can approach dismantling differently from someone confronting an apparently solid joint without records. A diagram identifying the location, diameter, and depth of concealed dowels may prevent unnecessary exploratory drilling.

Identification of the exact adhesive can inform solvent screening, temperature limitations, expected hardness, and likely removal strategy.

For this reason, documentation becomes increasingly important as material reversibility decreases. The more permanent the intervention, the stronger the obligation to tell the future practitioner exactly what was done.

AIC guidance explicitly requires permanent records of examination and treatment, including procedures, materials, composition, alterations, and recommendations for subsequent care (American Institute for Conservation, n.d.).

25.11. Retreatability as a Design Requirement

Technical Paper No. 3 therefore proposes that retreatability be evaluated during treatment planning rather than after a repair fails.

Before applying adhesive, the practitioner should be able to describe in reasonable terms how another conservator might approach the joint in the future.

For a tablet fracture, the answer may be that direct epoxy removal would be difficult and that future repair would probably have to work with the surviving bond unless failure itself created access.

For a B-72 joint, solvent-assisted separation may be plausible. For a limited-bond monument, lifting and progressive mechanical separation may be anticipated.

For a pinned connection, cutting or abandoning the embedded reinforcement may be more realistic than complete removal. If no future pathway can be identified, the degree of present-day necessity should be correspondingly higher.

The question is not whether the practitioner can guarantee successful retreatment decades later. It is whether today's repair unnecessarily closes options that could reasonably have remained open.

25.12. Conservation Implications for Reversibility

Reversibility should remain a major conservation objective, but not a simplistic pass-fail test for structural adhesives.

The strongest treatment principle is:

Use the most retreatable system that can reliably provide the required structural performance, and where irreversible intervention is necessary, limit its extent, preserve access where practical, and document it fully.

This position does not weaken the traditional conservation concern surrounding epoxy. It makes that concern more precise. A permanent material still carries a higher burden of justification than an equally effective retreatable alternative.

What this paper rejects is the assumption that permanence alone determines suitability regardless of joint geometry, structural demand, or the invasiveness of competing treatments.

26. Minimum Intervention and Necessary Permanence

26.1. Minimum Intervention Is Not Minimum Action

Minimum intervention is frequently expressed as one of the foundational principles of conservation. In practice, the phrase can be misunderstood. It does not mean doing as little as physically possible.

A fractured tablet left unsupported because bonding would introduce modern material has not necessarily been preserved through restraint. If the next moderate impact causes additional fragmentation, avoiding intervention merely postponed greater loss.

Likewise, a loose elevated monument component should not remain dangerously unstable simply because every effective connection is irreversible to some degree.

Minimum intervention is better understood as the least alteration necessary to achieve the legitimate preservation objective. This definition links restraint to performance. The treatment must accomplish enough. Beyond that point, additional intervention requires additional justification.

26.2. The Preservation Objective Must Be Defined First

Determining the minimum necessary intervention requires knowing what the treatment is intended to achieve.

Possible objectives include preventing collapse, returning a displaced component to stable bearing, reconnecting a broken tablet, preventing a fragment from falling, filling an internal void, restoring water management at a joint, or compensating for missing material. These objectives are not interchangeable.

A monument that merely needs stable resetting should not automatically receive the same structural intervention as a fractured elevated sculpture.

Likewise, restoring aesthetic continuity should not justify permanent structural materials where a more retreatable nonstructural fill would accomplish the visual objective.

AIC guidance requires a treatment plan to identify the objectives, justification, alternatives, and potential risks before intervention (American Institute for Conservation, n.d.).

That planning discipline is particularly useful in cemetery conservation because it makes the practitioner state why a permanent material is being introduced.

26.3. Necessary Permanence

Some structural repairs require permanence because the treatment's function depends upon maintaining reliable connection over long periods.

A thermosetting adhesive joining a fractured tablet is intended to remain stable through repeated environmental exposure. A stainless-steel pin securing an elevated element is not designed to detach periodically for conservation convenience.

A grout injected into an inaccessible internal void may need to remain in place because removing it would require recreating the original defect. The ethical question is not whether these treatments are permanent.

It is whether that permanence is **necessary and proportionate** to the preservation problem.

This paper uses the term **necessary permanence** for interventions in which a less permanent alternative cannot provide comparable preservation, safety, durability, or structural performance without introducing another equal or greater risk.

26.4. Permanence Requires a Burden of Justification

The more irreversible the intervention, the stronger its justification should be. That burden is best evaluated in relation to necessity, substrate condition, viable alternatives, the amount of original material permanently altered, the foreseeable failure mode, and the practical pathway for future retreatment.

A defensible treatment should address an active preservation or safety problem rather than appearance alone; the receiving stone should be capable of carrying the proposed load; less invasive alternatives should have been considered for adequacy rather than dismissed merely because they provide lower ultimate strength; and the practitioner should be able to identify what historic material will be altered permanently and how another conservator might approach the repair later. Framed this way, the questions are not bureaucratic obstacles but a disciplined basis for choosing permanent intervention.

26.5. Avoiding Treatment Can Also Be Harmful

The conservation community properly emphasizes risks created by intervention. Risks created by nonintervention deserve equal consideration. Open fractures admit water and allow pieces to move independently.

Loose fragments can fall. Rocking monument components can grind historic bearing surfaces against one another. Corroding metal can continue expanding.

Unstable leaning monuments can eventually collapse. Repeated temporary resetting may abrade surfaces more than one carefully designed durable repair.

AIC's conservation framework includes preventive care and intervention as parts of a continuum rather than treating nonintervention as inherently superior (American Institute for Conservation, n.d.). NPS cemetery guidance similarly emphasizes cyclical, sustainable, noninvasive care while also recognizing stabilization and repair as necessary when grave markers are threatened (National Park Service, n.d.-a).

Minimum intervention therefore requires comparison between the risks of acting and the risks of leaving the condition unchanged.

26.6. The Irreversibility of Repeated Failure

An overly weak repair can become cumulatively more destructive than one carefully limited permanent intervention.

Imagine a tablet repaired with an adhesive deliberately selected to fail easily. If the joint separates repeatedly during ordinary environmental exposure, each failure may remove loose grains, enlarge edges, introduce dirt into the fracture, require handling, and expose the stone to renewed cleaning and bonding.

After several cycles, considerably more original material may have been lost than would have been affected by one durable structural repair. This example does not justify maximum-strength epoxy. It demonstrates that premature failure is itself irreversible. Original stone lost during each episode cannot be recovered merely because the adhesive was soluble.

The service life of the treatment therefore belongs within conservation ethics. Durability and retreatability should be balanced rather than treated as opposing virtues.

26.7. Drilling Versus Surface Bonding

The comparison between pinning and adhesive repair demonstrates necessary permanence particularly clearly.

A drilled dowel permanently removes historic marble and introduces a rigid mechanical connection. A direct epoxy bond alters the fracture surfaces chemically but leaves the surrounding cross-section undrilled.

If both treatments provide adequate performance, the less invasive one should generally be preferred. That may be adhesive-only repair for a sound close-fitting tablet.

The answer changes when adhesive alone cannot provide sufficient structural capacity. Under that condition, the pin is not excessive merely because drilling is irreversible. Its permanence becomes structurally justified.

The same reasoning applies in reverse. Pinning a low broad monument simply because hardware appears more secure may represent unnecessary permanence if stable bearing and limited restraint already provide sufficient capacity.

Minimum intervention is therefore a comparison among adequate treatments. An inadequate alternative does not become preferable merely because it is less invasive.

26.8. Full Bonding Versus Limited Bonding

The same reasoning distinguishes continuous structural bonding from the GG limited-bond model.

If a monument component requires broad adhesive coupling because its geometry generates substantial tensile or overturning forces across the interface, full bonding may be justified.

If the same component already possesses broad stable compression and needs only modest supplemental restraint, bonding the entire interface permanently alters more historic material than the structural requirement appears to demand. In that latter condition, limited bonding offers a plausible application of minimum intervention.

The key word remains plausible until experimental validation defines the performance limits of the system. Minimum intervention should not be used as rhetorical justification for a treatment whose capacity has never been considered.

26.9. Intervention Area as an Ethical Variable

Conservation discussions frequently compare material chemistry but pay less attention to treatment area. Technical Paper No. 3 argues that area should itself be treated as an ethical and mechanical variable.

Two permanent materials can create very different degrees of intervention depending upon how much historic surface they occupy.

This provides a useful rule:

Once a permanent material has been justified, its application should still be limited to the area necessary for that function. A narrow fracture should not become a broad epoxy patch.

A localized restraint should not expand into a bedding layer without structural reason. A drilled pin hole should not be made larger than necessary for the selected reinforcement.

A consolidant should not be spread beyond the deteriorated zone merely because additional treatment is convenient. Permanent treatment should have boundaries.

26.10. Original Construction as Evidence, Not an Absolute Command

Minimum intervention often favors retaining or reproducing the original structural logic of a monument.

If a die originally relied primarily upon gravity, broad bearing, lead, and a traditional setting joint, restoring that relationship may be less invasive than introducing new pins or full epoxy bonding. Historical construction should nevertheless not become an absolute rule.

Original iron pins that corrode and split stone should not necessarily be reproduced in iron merely for authenticity. A monument whose historical foundation system has failed repeatedly may require carefully designed improvement.

A heavy elevated element whose original attachment is demonstrably inadequate for present public-safety conditions may require supplemental restraint.

Preservation respects original construction by understanding it first. It does not require repeating known failure mechanisms blindly.

26.11. Repairing Versus Improving

One of the more subtle risks in structural conservation is the desire to make a monument “better than new.”

Modern materials make this possible. Adhesives can create stronger bonds than original setting compounds. Stainless-steel reinforcement can provide greater restraint than historic iron or copper systems. Modern foundations can be substantially more rigid than nineteenth-century construction.

Improvement can be beneficial when it corrects a known damaging deficiency. It can become over-treatment when increased strength simply pushes future movement into historic material.

The objective should ordinarily be **restored adequate performance**, not maximum modernization.

A repaired monument should be stable, safe, and durable. It does not need to become a monolithic engineered structure merely because modern materials make that possible.

26.12. Visible Evidence of Repair

Minimum intervention should not be confused with making every repair invisible.

Aggressive grinding, polishing, coloring, or filling performed solely to conceal a repair can remove additional historic material and complicate future interpretation.

A well-executed adhesive joint should certainly avoid unnecessary visual distraction. Excess polymer, staining, gross misalignment, and conspicuous incompatible fills are undesirable.

Yet a subtle, identifiable repair line may be preferable to alteration undertaken to erase every sign that the stone was ever broken.

AIC guidance similarly recognizes the importance of documenting and, where appropriate, allowing compensations for loss to remain detectable rather than falsifying the history or physical character of the object (American Institute for Conservation, n.d.).

Cemetery monuments possess histories of damage and repair. Conservation should preserve dignity and legibility without requiring historical erasure.

26.13. The Option to Stop

One of the clearest expressions of minimum intervention is the willingness to stop treatment when conditions differ materially from expectations. A monument may reveal hidden cracks after lifting.

The presumed sound bearing surface may prove extensively deteriorated. An old iron pin may be larger or more corroded than anticipated.

The amount of Prutley required to stabilize the component may expand far beyond the limited-bond concept. The substrate may prove too friable for adhesive.

Under these conditions, continuing with the original plan simply because materials have already been prepared is poor conservation practice. Chapter 20 proposed GG stop criteria for precisely this reason.

A treatment plan is a reasoned proposal, not an obligation to complete a predetermined technique regardless of what the monument reveals.

26.14. Necessary Permanence and Public Safety

Safety presents the strongest case for accepting irreversible structural intervention.

An elevated stone component that can fall onto visitors, staff, volunteers, or neighboring monuments cannot be treated as though the preservation of every square centimeter of drilling surface outweighs the risk of collapse.

Where engineering analysis or competent field assessment establishes that positive restraint is necessary, mechanical anchorage may be appropriate even though it permanently alters the stone.

The same principle applies to removing dangerously unstable elements temporarily rather than attempting a minimally invasive repair in place. Conservation ethics include responsibility to people as well as objects.

The existence of safety consequences raises the required certainty of structural performance. It does not grant permission for indiscriminate reinforcement.

26.15. A Hierarchy of Intervention

The treatment framework developed in Chapter 20 can be restated ethically as a progression.

Where stable bearing and appropriate joint treatment are sufficient, additional adhesive should not be introduced merely out of habit. Where modest restraint is required, localized bonding should be considered before broader permanent bonding.

Where a structural fracture requires continuous adhesive, a thin controlled bond may be justified. Where adhesive cannot provide adequate stability, mechanical reinforcement becomes appropriate.

Where even reinforcement cannot be installed safely in deteriorated stone, external support, alternative presentation, or non-reassembly should be considered.

This is not a rule requiring every monument to proceed sequentially through four experimental treatments. It is a reasoning hierarchy that prevents greater intervention from becoming the default starting point.

26.16. Conservation Is Management of Future Risk

Necessary permanence is ultimately a risk-management concept. Every treatment redistributes risk. Weak treatment increases the risk of repeated separation.

Strong treatment may increase the risk of cohesive substrate failure. Pinning increases localized intervention while reducing release risk.

No intervention preserves original fabric today while potentially allowing ongoing deterioration tomorrow. A conservative treatment does not eliminate risk.

It selects the combination of present stability, future failure consequence, retreatability, and material loss that best preserves the monument over time.

This is why the paper's central question is not “Which material does the least today?”

It is:

Which intervention is likely to preserve the most historic material over the life of the treatment while providing the stability the monument actually requires?

26.17. Conservation Implications for Necessary Permanence

Permanent treatment should never be trivialized simply because a product is convenient or widely used.

Neither should it be rejected categorically when it provides a clearly justified structural benefit unavailable through less invasive means.

The most defensible position is:

Permanence is acceptable when it is necessary for preservation or safety, proportionate to the structural need, localized wherever practical, applied to substrate capable of receiving it, documented completely, and selected with deliberate consideration of future failure and retreatment.

This principle provides the ethical foundation for the workmanship standards addressed in Chapter 27. Once permanence has been justified, poor execution cannot be allowed to enlarge its footprint unnecessarily.

27. Workmanship and Quality Control

27.1. Material Selection Cannot Compensate for Poor Workmanship

The preceding chapters have examined adhesive chemistry, marble condition, joint geometry, bonded area, bearing, environmental exposure, reversibility, and failure hierarchy. Each variable matters. None eliminates the importance of workmanship.

A theoretically ideal adhesive can perform poorly if mixed incorrectly, applied to contaminated stone, used outside its temperature range, allowed to cure incompletely, or forced into an inappropriate bond geometry.

Conversely, experienced workmanship cannot transform an inherently unsuitable material into a conservation-compatible system. Materials and technique interact.

For this reason, workmanship should not be treated as an informal craft factor outside the scientific analysis. It is a **controlled treatment variable**.

The same repair system performed inconsistently by different practitioners may produce greater variation than the difference between two competing adhesives.

27.2. Product Instructions and Conservation Judgment

Manufacturer instructions provide essential information about mixing ratios, working time, temperature limits, surface cleanliness, cure, and product handling. They are written primarily to optimize the performance of the commercial adhesive.

Conservation introduces an additional responsibility: recommendations intended to maximize adhesion to new fabricated material may not always be appropriate for irreplaceable historic surfaces.

Akepox 5010 instructions, for example, recommend thoroughly cleaning and slightly roughening the surfaces to be bonded. The same data sheet identifies a 2:1 ratio of components A and B, approximately 20–30 minutes working time at 20°C, movement after roughly 6–8 hours, further processing after about 12–16 hours, and maximum stability after seven days. AKEMI also warns against application below 10°C because curing will be insufficient (AKEMI GmbH, 2022; see Appendix J, Section J.2).

The mixing ratio and temperature requirements should be followed closely. The recommendation to roughen requires conservation interpretation.

A freshly broken historic marble fracture should not automatically be sanded or ground merely because roughness would increase maximum industrial adhesion. Original fracture texture already provides significant mechanical engagement, and deliberate removal of

historic material may be unnecessary. Manufacturer guidance and minimum-intervention principles must therefore be read together.

27.3. Surface Cleanliness

Adhesive should bond to coherent stone rather than to loose dirt, biological residue, deteriorated mortar, grease, detached grains, or incompatible previous repair material.

Pratley's current instructions similarly require bonding surfaces to be free of loose dirt, rust, paint, oil, and grease. The manufacturer notes that abrasion can improve adhesion to smooth surfaces (Pratley, 2023; see Appendix J, Section J.8).

Again, the conservation requirement is **clean and coherent**, not aggressively abraded.

The amount of cleaning appropriate to a polished modern stone seam differs from that appropriate to a nineteenth-century fracture containing fragile original tool marks, patina, or granular marble. Loose material that would prevent reliable bonding should be removed. Sound original marble should not.

27.4. Removing Previous Repair Material

Old repairs often present the most difficult surface-preparation problem. Failed epoxy, polyester, silicone, Portland cement, mortar, putty, or caulk can interfere with accurate fit and new adhesion.

Complete removal may be impossible without cutting into the original fracture surface. The appropriate objective is not automatically a pristine white marble surface.

It is sufficient removal of failed or incompatible material to permit reliable seating and load transfer while preserving as much original fracture geometry as practical.

Stable remnants of an earlier repair may sometimes be retained if removal would cause greater damage and if they do not interfere materially with the new system. These decisions should be documented because the resulting substrate is no longer simply original marble.

27.5. Dry Fitting Before Mixing Adhesive

No structural adhesive should be mixed until the repair has been dry-fitted sufficiently to establish alignment, bearing, working sequence, lifting procedure, and adhesive location.

This is especially important with two-component systems whose working time begins as soon as mixing occurs. Dry fitting allows unexpected problems to be solved without a curing adhesive imposing a deadline.

Clamp locations, lifting points, wedges, temporary supports, cleanup tools, photography, and personnel responsibilities should all be established beforehand. This may appear procedural rather than scientific.

In practice, it directly affects bond quality because rushed positioning produces uneven bond lines, poor alignment, excessive squeeze-out, and unnecessary adhesive spread.

27.6. Measuring Components Accurately

Two-component adhesives depend upon correct resin-to-hardener proportion.

Akepox 5010 requires two parts component A to one part component B by volume or weight. AKEMI warns that excess resin or hardener alters mechanical and chemical performance and may contribute to discoloration (AKEMI GmbH, 2022).

Pratley Standard Setting Putty requires equal portions of its two sticks, kneaded until the mixture develops uniform color without streaking (Pratley, 2023).

Approximate visual mixing may be acceptable only where the manufacturer specifically designs the product for that method. Where ratios are specified by weight or volume, accurate proportioning should become part of field quality control.

A technically excellent resin mixed at an incorrect ratio is no longer the material characterized in the manufacturer's data sheet.

27.7. Complete Mixing

Correct proportion does not guarantee correct cure if components are not mixed thoroughly. Unmixed resin or hardener can create soft zones, surface tack, discoloration, reduced strength, and chemical instability.

Pratley's instruction to continue kneading until the color is uniform provides a straightforward visual control (Pratley, 2023).

Liquid and gel epoxies require equally deliberate mixing, including scraping the sides and bottom of the mixing container where hand mixing is used.

Cartridge systems with static mixing nozzles can improve consistency by controlling ratio and mixing simultaneously, but initial unmixed material should be purged according to the product procedure before the bond is made. Quality control should assume that mixing is a structural operation.

27.8. Batch Size

Mixing more adhesive than needed can create several problems.

Larger epoxy masses can generate more exothermic heat during cure, shorten effective working time, encourage unnecessary application, and produce waste.

The amount prepared should correspond reasonably to the planned bonded area. This principle has particular conservation significance in limited-bond systems. The presence of unused mixed Pratley should never become a reason to add additional pads.

The treatment plan defines the amount of permanent intervention. The amount of material remaining in the mixing tray does not.

27.9. Temperature

Temperature affects both working time and cure.

Akepox 5010 demonstrates the relationship clearly. AKEMI reports approximately 60–70 minutes working time at 10°C, 20–30 minutes at 20°C, 10–15 minutes at 30°C, and 5–10 minutes at 40°C. The manufacturer states that the product should not be used below 10°C because it will not harden sufficiently. These differences matter greatly in cemetery work (AKEMI GmbH, 2022).

A procedure rehearsed comfortably on a 20°C day may become rushed in direct summer heat. Conversely, a cool autumn repair may remain vulnerable to movement much longer than expected.

The temperature of the stone, not merely the reported air temperature, should be considered. Sunlit marble can become substantially warmer than shaded ambient air. Field records should therefore include approximate air and stone conditions where feasible.

27.10. Moisture Condition

Damp-tolerant adhesives provide useful resilience but should not encourage careless bonding of wet stone.

Akepox 5010 is described as adhering well to slightly humid stone. Pratley Putty can cure underwater and is explicitly promoted for such applications. These product capabilities are relevant (AKEMI GmbH, 2022; Pratley, 2023).

They do not eliminate the conservation concerns associated with moisture, salts, freeze-thaw exposure, and continuing water movement through the substrate.

Where practical, marble should be allowed to reach a stable, reasonably dry surface condition before structural repair. Adhesive tolerance for residual moisture should function as a safety margin, not as permission to ignore active dampness.

27.11. Controlling Bond-Line Thickness

A close-fitting fracture should be returned as closely as practical to its original geometry.

The objective is neither to squeeze out every trace of adhesive nor to intentionally hold the pieces apart to create a visible resin layer. Too little adhesive can produce dry areas. Too much increases permanent polymer volume and may alter alignment.

Clamp or strap pressure should therefore bring the fracture into accurate registration without being so aggressive that most of the resin is forced out.

For horizontal putty pads, the opposite issue applies. The putty should not become the element that determines the full joint thickness if lead and stone bearing are intended to do that work. Bond-line control is thus specific to the repair geometry.

27.12. Adhesive Coverage

A structural fracture requires sufficiently complete wetting to avoid unbonded pockets that concentrate stress.

A limited-bond monument requires deliberately incomplete **area** coverage by design. These statements are not contradictory.

Within each intended adhesive region, coverage should be reliable and continuous. Across the overall monument interface, permanent adhesive should remain confined to the area justified by the treatment plan.

This distinction should be emphasized during training because “use adhesive sparingly” can otherwise be interpreted incorrectly as applying a thin, inadequate film within a bond that actually requires full wetting. Minimum intervention concerns the intended treatment area, not poor application within that area.

27.13. Location Control for Pratley Pads

Pratley pads in a limited-bond system should be predetermined during dry fitting and documented before the component is lowered. Placement should avoid fragile edges, visible carved zones, major existing cracks, and severely deteriorated surfaces.

Pads should be positioned so that stable stone surrounds the loaded region. The field team should resist spontaneous changes during final setting unless an unexpected condition requires reassessment.

If the required pad area expands substantially because the monument will not remain stable otherwise, the work should stop and the bearing or structural concept should be

reconsidered. Limited-bond repair becomes meaningless if “localized” adhesive expands until most of the interface is permanently bonded.

27.14. Lead Placement and Bearing Quality

Lead wedges should be adjusted gradually.

Hammering or forcing wedges aggressively beneath brittle marble can chip edges, induce point loads, or shift the component unexpectedly. The final monument should not rock.

Lead should not protrude conspicuously where it can be displaced easily, nor should narrow wedges be the only meaningful points supporting a heavy upper component.

The setter should verify the overall bearing relationship before adhesive cure prevents additional adjustment. This is another reason dry fitting is indispensable.

27.15. Clamping and Restraint

Tablet repairs may require straps, clamps, temporary frames, or other means of maintaining alignment during cure. Clamping force must be distributed through padded contact surfaces.

A clamp capable of holding two pieces together is also capable of crushing weakened marble or damaging inscription. The objective is positional restraint rather than maximum compression.

The repair should be checked from both faces and edges before cure progresses beyond the adjustment period. Even small misalignment can become permanent once a structural epoxy has cured.

27.16. Controlling Squeeze-Out

Excess adhesive at the joint should be controlled while it remains safely removable. Akepox squeeze-out spread across weathered marble unnecessarily enlarges the irreversible treatment area.

Pratley instructions likewise direct users to remove excess material and wipe surrounding surfaces before cure (Pratley, 2023). Cleanup must be performed conservatively.

Solvents should not be spread broadly across porous historic stone merely to create a perfectly invisible seam. Aggressive scraping can remove marble grains. Smearing partially cured resin can produce staining worse than a small controlled residue. Preventing excess application is preferable to aggressive cleanup.

27.17. Avoiding Adhesive Smears on Exposed Marble

One of the clearest differences between professional conservation-oriented adhesive use and general construction practice is control of the treatment footprint.

Disposable barriers, masking strategies compatible with the stone, carefully positioned application tools, and preplanned cleanup can help prevent resin from reaching visible areas.

Any masking material should itself be evaluated for adhesion and residue. Strong pressure-sensitive tapes can remove friable grains or leave adhesive on porous marble.

Where masking presents greater risk than careful freehand application, it should not be used simply for convenience. Workmanship remains object-specific.

27.18. Cure Protection

A repair remains vulnerable after it appears hard enough to touch.

Akepox 5010, for example, reaches maximum stability after approximately seven days at 20°C even though bonded components may be moved sooner. Pratley Standard Setting Putty is described as reaching full strength after approximately 24 hours under room-temperature conditions, with timing dependent upon temperature and quantity (AKEMI GmbH, 2022; Pratley, 2023). Early movement can disrupt an adhesive that appears superficially cured.

Monuments should therefore be protected from unnecessary handling, cleaning, vibration, or repositioning during the initial cure period.

Where the repair relies upon temporary bracing, that bracing should remain until the adhesive has reached the required condition for unsupported service.

27.19. Environmental Protection During Cure

Rain, direct intense sunlight, freezing temperatures, and rapid temperature changes can complicate field curing.

A temporary shelter may be appropriate where it protects the repair without creating unsafe rigging or trapping excessive heat. Cold-weather repair should be avoided where product temperature requirements cannot be maintained.

Hot-weather work may require scheduling earlier in the day, shading materials, or reducing batch size to preserve adequate working time.

The treatment schedule should follow the material. The material should not be expected to accommodate an arbitrary work schedule.

27.20. Contamination Between Material Systems

Repairs combining epoxy, B-72, Pratley, lead, mortar, and monument setting compound require control over the sequence in which materials contact the stone. Setting compound accidentally smeared onto an area intended for Pratley could compromise adhesion.

B-72 intervention layers must dry adequately before a secondary adhesive is applied. Mortar residue can interfere with epoxy bonding. Silicone contamination can create severe adhesion problems.

Each layer should therefore be applied according to a deliberate sequence with the intended bonding zones protected from incompatible materials. Combined systems increase conservation flexibility. They also increase workmanship complexity.

27.21. Quality Control Hold Points

For more complex structural repairs, several **hold points** should be established where the team deliberately verifies conditions before moving forward.

The most useful occur after examination, after cleaning, after dry fitting, after bearing adjustment, immediately before adhesive mixing, after adhesive placement but before final lowering where geometry permits, after final alignment, and after cure. These hold points need not become cumbersome formal inspections for every small repair.

Their purpose is to prevent irreversible steps from occurring before the assumptions underlying them have been checked. Once epoxy is mixed or a heavy die is lowered onto putty, the ability to reconsider decreases rapidly.

27.22. Photographic Quality Control

Photography provides more than final documentation.

Images taken during the repair allow later verification of pad location, adhesive coverage, pin position, hidden cracks, bearing surfaces, and previous repairs that disappear after reassembly.

For limited-bond monuments, a photograph of the final Pratley pad arrangement before lowering the upper stone should be considered a standard quality-control record. A scale or other dimensional reference should be included where practical.

Consistent orientation matters. A future practitioner should be able to determine which side of the photographed interface corresponds to the monument's front, back, left, and right. Good documentation begins with workmanship.

27.23. Mixing and Material Records

Where practical, treatment records should identify manufacturer, product name, lot or batch information, expiration or purchase condition, mixing ratio, additives or pigments, and approximate quantity used.

This level of detail can appear excessive until a problem develops years later. If several repairs using one batch discolor or fail, batch information becomes valuable.

If a formulation changes over time, identifying the exact product date can prevent future conservators from assuming that present-day specifications describe the historic repair. A product name alone may not be sufficient over a fifty-year treatment horizon.

27.24. Personnel and Training

Structural monument repair should not depend upon one practitioner's undocumented intuition.

Teams should understand why each material is being used, what its limitations are, and what conditions require stopping the procedure.

This is especially important in volunteer organizations where participants may possess very different levels of experience. Tasks can be divided appropriately.

One person may control mixing. Another may monitor alignment. Another may operate lifting equipment. Another may document the work.

Clear responsibility reduces the likelihood that everyone assumes someone else is checking the critical detail. Training should emphasize principles rather than memorized recipes.

A trained practitioner should understand why a thin tablet bond differs from a horizontal Pratley pad, not merely know that one gets “5010” and the other gets “Pratley.”

27.25. Workmanship as an Experimental Variable

The experimental program proposed in Chapters 21–24 should also examine workmanship sensitivity.

A material that performs exceptionally when mixed and applied under tightly controlled laboratory conditions but fails dramatically with small deviations may be less attractive for routine field work than a somewhat lower-performing material with greater tolerance.

Variation in ratio, moisture, temperature, bond width, or surface condition can therefore be explored in secondary experiments after baseline performance is established. This should not be interpreted as designing products around careless practice.

It recognizes that historic cemetery conservation occurs outdoors under conditions that cannot be controlled as completely as a fabrication shop or laboratory. A robust treatment system should possess reasonable practical tolerance.

27.26. Workmanship and the Failure Hierarchy

Poor workmanship can reverse the intended failure hierarchy. A localized pad applied too close to an edge can produce breakout. Excess epoxy spread across a tablet can enlarge the future fracture zone. A poorly seated component can place adhesive into sustained tension instead of allowing stone bearing to carry compression.

Incorrect ratio can produce weak adhesive failure. Overly strong clamping can damage marble before the adhesive has cured. Insufficient drying of an intervention layer can alter its behavior. The failure hierarchy therefore begins during application. It cannot be designed on paper and assumed to survive careless execution.

27.27. Proposed Quality-Control Principle

The appropriate workmanship principle can be stated simply:

Every irreversible step should be preceded by verification that the stone condition, geometry, material, quantity, and environmental conditions still match the treatment plan.

This principle encourages deliberate work without turning conservation into procedural bureaucracy. Historic stone does not reward speed for its own sake. Accuracy, restraint, and the willingness to stop are structural qualities.

28. Documentation and Monitoring

28.1. Documentation Is Part of the Repair

A completed monument repair contains information that becomes invisible almost immediately.

Adhesive pads disappear beneath the stone. Lead wedges may be concealed by perimeter material. Pin holes vanish within the joint.

Intervention layers cannot be seen. Previous fractures become difficult to distinguish from fills. Materials weather until their original appearance changes.

Without records, future conservators must reconstruct this history through observation, speculation, and sometimes destructive investigation.

Documentation therefore should not be regarded as paperwork accompanying the treatment. It is one of the treatment materials. It preserves knowledge that physical intervention may otherwise erase.

AIC guidance places a strong obligation on conservation practitioners to create accurate, complete, durable written and pictorial records before, during, and after treatment, including materials, techniques, alterations, and recommendations for future care (American Institute for Conservation, n.d.).

28.2. Documentation Before Treatment

Pre-treatment documentation establishes the baseline against which both the intervention and future condition can be judged.

The record should identify the monument, location, orientation, type, dimensions, material, visible deterioration, fractures, previous repairs, biological growth, foundation condition, joint condition, and surrounding environmental factors relevant to the work. Overall photographs should establish context. Closer photographs should record each treatment area.

A scale should be used where dimensional interpretation matters. The location of detached fragments should be documented before movement.

NPS cemetery-preservation guidance emphasizes exactly this type of recurring condition assessment. It recommends recording marker type, materials, orientation, dimensions, deterioration, earlier repair information, and both overall and detail photography (National

Park Service, n.d.-c). The pre-treatment record is especially important when dismantling will reveal conditions that cannot later be reconstructed.

28.3. Documenting the Failure Mechanism

The treatment record should distinguish observed damage from the practitioner's interpretation of what caused it.

For example:

Observation: die displaced approximately 12 mm toward the east; failed setting material present along west edge; base appears level.

Interpretation: lateral displacement probably resulted from impact or previous handling rather than continuing foundation rotation. Keeping observation and interpretation separate improves future review.

If later evidence shows that the foundation was actually moving, the original record remains useful because it shows what was known at the time.

The same distinction should apply to cracks, staining, biological growth, and previous repairs. Documentation should preserve evidence rather than simply defend the selected treatment.

28.4. Recording Previous Interventions

Existing repair materials should be recorded before removal whenever practical.

This includes pin materials, old epoxy, polyester, cement, mortar, lead, caulk, grout, consolidants, repair mortars, and improvised repairs. Photographs should show their position relative to original stone.

Where identifiable material is removed, a small, labeled sample may occasionally be worth retaining for significant monuments or research projects, subject to appropriate permission and storage. Previous repairs form part of the monument's physical history.

Even failed interventions can reveal how loads moved, where deterioration concentrated, and which materials did or did not survive the environment.

28.5. Documentation During Disassembly

Once a multi-piece monument is lifted, previously concealed evidence should be recorded before cleaning.

This stage can reveal original tool marks, lead, mortar, pin holes, staining, previous adhesive, bearing points, hidden cracks, sockets, construction marks, and voids.

Photographs should identify orientation clearly. A simple directional convention—front, back, left, right—can make the record far more usable later.

If lead wedges or pins are removed, their original locations and dimensions should be recorded. A historic pin system should not disappear from the record merely because a new treatment replaces it.

28.6. Treatment Plan

Before irreversible intervention, a concise treatment plan should identify what is proposed and why.

The plan should state the treatment objective, selected structural level, materials proposed, whether adhesive is structural or supplemental, whether drilling is planned, expected pad or pin locations, perimeter treatment, and significant alternatives considered. Potential risks should be acknowledged.

AIC guidance specifically calls for treatment planning after examination and before treatment, including justification, objectives, alternatives where feasible, and potential risks (American Institute for Conservation, n.d.). For routine GG work, this need not require a lengthy formal report.

A standardized digital treatment form could capture the same reasoning efficiently. What matters is that the decision exists before the permanent material is applied.

28.7. Material Identification

Treatment records should identify materials precisely. “Epoxy” is not sufficient. “Mortar” is not sufficient. “Lead” may not be sufficient where alloy or form matters.

A record should instead identify products such as Akepox 5010, Pratley Standard Setting Putty, Heritage IG10, Paraloid B-72 with the solvent and concentration used, or the specific mortar formulation. Where two-component products are used, the recorded mixing ratio should match the procedure.

Pigments, fillers, aggregate, additives, and intervention layers should be identified. The approximate location and extent of each material is equally important.

28.8. Adhesive Location Maps

For limited-bond systems, an adhesive-location map should become standard.

A simple plan-view diagram of the monument interface can record pad number, approximate size, distance from edges, lead position, and any excluded areas associated with cracks or deteriorated stone. The drawing does not need engineering drafting precision. Its purpose is future legibility.

Photographs should supplement the map, not replace it entirely. Photographs can be lost, cropped, or viewed without clear orientation. A diagram labeled **FRONT** can remain understandable decades later.

This requirement is particularly important because the conservation advantage of localized adhesive partly depends upon future practitioners being able to find it. Unknown localized adhesive is less retreatable than documented localized adhesive.

28.9. Pin Documentation

Where pins are used, records should include material, diameter, approximate length, hole diameter, embedment depth, orientation, adhesive or grout, and position.

Photographs taken before final assembly should show the hole and reinforcement. If an existing historic hole is reused, that fact should be recorded explicitly.

This allows future practitioners to distinguish old material from new intervention and may prevent additional unnecessary drilling.

Mechanical reinforcement is one of the most consequential hidden alterations to a monument. It warrants commensurate documentation.

28.10. Bearing Documentation

The location and form of permanent bearing materials should also be recorded. Lead wedges should be mapped or photographed.

Mineral bedding should be identified by composition and extent. If original stone-to-stone bearing was restored without continuous bedding, that condition should be noted.

These observations are important because a future shift in joint width or lead extrusion may be interpretable only when the original bearing configuration is known. A record of the adhesive without the bearing system would describe only part of the structural repair.

28.11. Environmental Conditions During Treatment

Temperature, recent precipitation, obvious stone dampness, direct sunlight, and other conditions affecting cure should be recorded at least approximately for structural adhesive treatments. This is particularly valuable where a later failure raises questions about cure.

Akepox 5010's working and curing behavior changes significantly with temperature, and the manufacturer warns against use below 10°C. The treatment record does not need to become a meteorological report.

It should contain enough information to establish that the material was used within appropriate conditions. Where actual stone temperature is measured, that information is more useful than ambient air temperature alone.

28.12. Cure and Completion Record

The date and approximate time of final bonding should be recorded, along with when temporary restraint was removed and when the monument returned to normal service. Unexpected conditions during cure should be noted.

These might include rain, temperature drop, movement, a disturbed brace, additional adhesive placement, or corrections made before final set.

The completed repair should then be photographed from the same viewpoints used before treatment wherever practical. Matched images greatly improve long-term monitoring.

28.13. Treatment Report

The final treatment report should summarize what was found, what was done, why it was done, what materials remain within the monument, and what should be monitored.

AIC guidelines specifically identify subsequent-care recommendations as part of treatment documentation (American Institute for Conservation, n.d.). For a typical GG structural repair, the report need not be academically long. Completeness is more important than length.

A concise two-page record with strong photographs, a pad-location diagram, product information, and monitoring recommendation can be more valuable than a long narrative that omits where the adhesive was placed.

28.14. Preservation of the Records

Documentation provides little future value if it exists only on one volunteer's phone or one laptop. NPS guidance recommends maintaining copies of cemetery documentation in more than one location and recognizes the long-term value of condition records to preservation planning (National Park Service, n.d.-c).

Conservators should therefore maintain a central treatment archive with reliable backup. Records should be searchable by cemetery, monument, individual name, date, material, and treatment type where practical.

A copy or summary should also be provided to the cemetery owner, municipality, church, historical organization, or other responsible custodian when appropriate. The ideal outcome is for treatment information to remain associated with the monument even if the individuals who performed the repair are no longer available.

28.15. Monitoring Begins with a Baseline

Monitoring is meaningful only when the post-treatment condition has been documented precisely enough to identify change.

Final photographs should show joint width, alignment, repaired fracture, perimeter material, visible lead if any, and adjacent cracks.

Measurements may include plumb, tilt, or joint width where these conditions are relevant. The objective is not to prove that the repair looks excellent immediately after completion.

It is to establish what “normal” looked like on the day the repair entered service. Future movement can then be identified rather than remembered subjectively.

28.16. What Should Be Monitored

Monitoring should extend beyond the adhesive seam.

Relevant observations include alignment, tilt, joint opening, renewed rocking, displacement, perimeter cracking, adhesive discoloration, staining, biological growth, efflorescence, salt deposits, new fractures, spalling, edge breakout, lead extrusion, foundation settlement, and changes in drainage. This whole-system view follows directly from the paper's structural argument.

A monument may retain an intact adhesive bond while the foundation changes or marble fractures elsewhere. Monitoring only whether “the glue held” would miss the more important conservation outcome.

28.17. Proposed Monitoring Intervals

NPS documentation guidance recommends recurring cemetery condition assessment, preferably on an annual spring cycle, so that deterioration and unstable conditions can be identified systematically (National Park Service, n.d.-c).

For structural adhesive repairs, a more focused initial schedule is reasonable because early field performance can reveal settling, cure-related movement, or unexpected environmental effects.

A proposed Gravestone Guardians monitoring sequence could include an initial post-cure record, inspection after the first major seasonal cycle, approximately one year after repair, and then incorporation into the cemetery's regular annual or cyclical assessment. High-risk, experimental, or particularly significant repairs may merit more frequent observation.

A stable repair does not require intensive inspection forever. Monitoring frequency should decline as confidence in performance increases unless conditions change.

28.18. The First Winter as a Useful Observation Point

For repairs in cold climates, the first winter provides an important early exposure period. The monument experiences freezing conditions, moisture, thermal contraction, snow, ice, and spring thaw.

An inspection after this first full seasonal cycle can reveal perimeter cracking, slight movement, unexpected moisture patterns, staining, lead movement, or crack development before years of exposure accumulate.

Such inspection should not be framed as an expectation that a properly completed repair will fail during its first winter. It is an opportunity to establish whether the real environment is behaving as assumed during treatment selection.

28.19. Monitoring Experimental Repairs

Repairs representing new or insufficiently validated methods should receive more systematic monitoring than mature procedures.

Early B-72 intervention-layer trials, alternative adhesive pads, new bearing materials, or modified perimeter systems should be identified clearly as monitored treatments. Comparable conventional repairs should ideally be tracked alongside them.

Field monitoring will never replace controlled laboratory testing because monuments differ too much for simple causal comparison. It can reveal whether laboratory concerns actually emerge outdoors.

The relationship should operate in both directions. Laboratory experiments inform field work; field observations generate the next laboratory questions.

28.20. Photographic Repeatability

Repeat photography becomes far more useful when images are taken from similar positions, distances, and orientations.

A small reference diagram or recorded camera direction can facilitate future comparison. Close-up photographs should include a scale where movement or crack growth is being monitored.

Modern digital imaging also allows transparent overlays between years, making small changes easier to detect. Photographic consistency should be prioritized over artistic presentation. The purpose is evidence.

28.21. Crack Mapping

Important cracks adjacent to structural repairs should be mapped or measured. The width need not be measured with laboratory precision unless the project requires it.

The record should make it possible to determine whether a crack existed before treatment, whether it has extended, and whether new cracking originates from the repair zone.

This is especially important for Akepox 5010 tablet repairs because crack migration adjacent to a strong bond represents one of the central failure concerns examined in this paper.

Without baseline documentation, a later crack can easily be attributed to the repair even if it existed beforehand. Conversely, a new crack can be overlooked if no earlier record exists.

28.22. Recording Maintenance Rather Than Calling It Failure

Perimeter joint renewal should be recorded separately from structural repair failure.

If monument setting compound requires replacement after a period of exposure while the bearing and structural restraint remain sound, that condition may represent expected maintenance within the intended failure hierarchy. The same applies to sacrificial lime pointing.

Maintenance records should show what material was removed and replaced, whether structural movement was observed, and whether the concealed system required disturbance.

This prevents future analysis from interpreting every joint renewal as evidence that the original repair failed prematurely. A maintainable system is expected to be maintained.

28.23. Trigger Conditions for Reassessment

Routine monitoring should identify conditions that require more than ordinary maintenance.

These include new structural cracking, progressive tilt, repeated opening of the same joint, significant lead extrusion, displacement, substrate loss around adhesive, expanding staining, persistent moisture concentration, visible pin-related cracking, or recurrence of the original failure mechanism.

When such changes appear, additional adhesive should not be applied reflexively. The monument should return to the assessment process established in Chapter 18.

A failed or changing treatment provides new information. The second intervention should respond to that information rather than simply strengthening the first repair.

28.24. Documenting Failure

When a repair fails, documentation becomes especially valuable.

The monument should be photographed before dismantling wherever safety permits. Failure surfaces should be recorded before adhesive is removed.

Residue on both sides of the joint can reveal whether failure was adhesive, cohesive within the polymer, cohesive within marble, or mixed. Fragments should be retained and mapped where practical. The quantity and depth of stone loss should be noted.

These observations can contribute directly to the failure taxonomy and research framework developed in Chapters 17 and 23. A failed field repair is unfortunate. An undocumented failed repair wastes an opportunity to learn from it.

28.25. Creating a Gravestone Guardians Treatment Database

The accumulated GG repair record could eventually become a significant source of field evidence.

A standardized database might track monument material, configuration, stone condition, treatment level, adhesive, bonded geometry, pinning, bearing materials, perimeter material, date, environmental exposure, observed movement, retreatment, and failure mode.

Over time, patterns may emerge—for example, localized Pratley pads may perform well on low dies yet show repeated edge loss above a particular geometry; Akepox 5010 tablet joints may remain stable while failures cluster in severely sugared stone; or particular perimeter compounds may show predictable maintenance intervals. Such patterns cannot be discovered reliably from memory or social-media photographs alone; structured records transform field experience into analyzable evidence.

28.26. Negative Results Belong in the Record

Organizations naturally document successful projects more enthusiastically than unsuccessful ones. Research and conservation improve only when both are retained.

A treatment that stains, releases early, proves impossible to retreat, or produces stone loss should remain in the database. The same is true of treatments abandoned after dry fitting or assessment.

Recording why a material was **not** used can be as valuable as recording the material that was selected.

This transparency protects against institutional memory gradually favoring only the successes and forgetting the conditions under which a technique performed poorly.

28.27. Documentation and Accountability

Good records also clarify the limits of what a treatment was intended to accomplish.

If a low monument was deliberately reset using GG Level 2 limited restraint because its geometry did not justify pins, the treatment record should state that reasoning.

If a later extraordinary impact destroys the monument, future reviewers can distinguish an event beyond the intended service condition from ordinary treatment failure.

Likewise, if a repair was explicitly experimental, that status should be documented. Accountability is strengthened by stating assumptions before results are known.

28.28. Documentation as Knowledge Transfer

The most enduring value of treatment records may ultimately be educational.

Future Gravestone Guardians volunteers, cemetery custodians, conservators, engineers, researchers, and monument setters can examine why particular decisions were made and whether those decisions performed as intended.

A treatment record therefore serves three timeframes simultaneously. It describes what existed before intervention. It explains what the present practitioner changed. It provides evidence for the person who must make the next decision.

That continuity is especially important in cemetery conservation because monuments routinely outlive the organizations and individuals caring for them.

28.29. Monitoring as Preventive Conservation

Monitoring should not be seen merely as waiting for a repair to fail. It is preventive conservation.

Identifying modest foundation movement before a joint breaks, renewing a perimeter compound before bulk water enters, correcting drainage before freeze-thaw damage increases, or recognizing a small crack before a heavy component becomes unstable can prevent the need for another major structural intervention.

NPS cemetery-preservation guidance explicitly emphasizes recurring condition assessment as a means of identifying unstable conditions, prioritizing maintenance, and developing preservation plans (National Park Service, n.d.-c).

A durable adhesive is useful. A monitoring program capable of preventing the adhesive from ever being asked to resist inappropriate loads is better.

28.30. The Continuum of Care

The modern conservation concept of a continuum of care is particularly appropriate to cemetery monuments. A repair is not a permanent endpoint.

The monument continues to exist within soil, weather, vegetation, public use, maintenance activity, and changing material condition.

AIC guidance recognizes preventive care, examination, treatment, documentation, and future intervention as connected responsibilities rather than isolated events (American Institute for Conservation, n.d.). The GG limited-bond model should be understood within that same continuum. A monument is assessed.

The least invasive adequate intervention is selected. Workmanship controls the permanent treatment footprint. The intervention is documented. The monument is monitored.

Maintenance is performed when needed. When conditions change, treatment is reconsidered using the evidence accumulated since the previous repair.

This cycle is more conservation-oriented than any claim that one adhesive, pin, mortar, or setting compound can permanently solve the monument.

28.31. Proposed Documentation Standard

The practical result of this chapter should ultimately be a standardized **GG Structural Treatment Record** containing five connected sections:

Identification and Pre-Treatment Condition would document monument location, material, configuration, dimensions, photographs, previous repairs, deterioration, foundation, and probable failure cause.

Treatment Rationale would identify the selected GG intervention level, structural objective, alternatives considered, and reason for the material choice.

Treatment Execution would record bearing, lead, adhesive or grout, pad or pin geometry, perimeter material, environmental conditions, workmanship observations, and deviations from the original plan.

Post-Treatment Baseline would document final alignment, joint appearance, photographs, crack map, and recommendations for subsequent care.

Monitoring History would provide dated entries for inspections, maintenance, movement, staining, new fractures, retreatment, or failure. This structure keeps the documentation focused on conservation decisions rather than turning it into a generic project log.

28.32. Documentation as Part of Retreatability

The connection between Chapters 25 and 28 should be explicit. Chemical reversibility is a property of materials. Mechanical retreatability is partly a property of geometry.

Informational retreatability is a property of documentation. A future practitioner who knows where the permanent intervention lies has more options than one who does not.

This provides a third dimension to the paper's treatment philosophy. The most retreatable structural repair is not merely the one that can theoretically be dissolved.

It is the one whose construction can be understood, accessed, and altered in the future with the least avoidable loss of original material.

28.33. Preliminary Gravestone Guardians Position

Structural monument conservation should be treated as a continuing management responsibility rather than a sequence of isolated repairs. Workmanship determines whether the material selected on paper performs as intended in the stone.

Documentation preserves information that physical intervention may otherwise erase. Monitoring identifies when the assumptions underlying the treatment begin to change.

Together, these practices complete the limited-bond philosophy developed throughout Technical Paper No. 3. The goal is not merely to create a strong joint.

It is to create a repair whose materials are appropriate, whose permanent footprint is controlled, whose construction remains understandable, whose future condition can be measured, and whose next intervention—whenever it becomes necessary—can begin with more knowledge than the intervention that came before it.

29. Findings and Discussion

29.1. Reframing the Structural-Adhesive Question

The investigation developed throughout this paper began with an apparently straightforward conservation controversy: whether modern high-strength adhesives are mechanically inappropriate for historic marble because their tensile strength may exceed that of the weathered stone they are intended to repair. That concern is neither trivial nor unfounded. A structural adhesive capable of remaining intact while original marble fractures around it can reverse the conservation hierarchy traditionally sought in repair, making irreplaceable historic fabric sacrificial to a modern intervention. Yet the evidence reviewed in this study demonstrates that the problem cannot be understood adequately through adhesive tensile strength alone. Historic marble is mechanically variable, adhesive joints are geometrically complex, environmental exposure changes both the stone and polymer over time, and the location of failure depends upon the interaction of substrate cohesion, adhesive properties, bond width, bonded area, loading direction, restraint, and surrounding support.

This broader interpretation does not weaken the traditional conservation concern regarding overly strong repairs. It makes that concern more mechanically precise. The relevant question is not whether the numerical tensile strength printed on a technical data sheet exceeds a published strength value for marble. Such comparisons frequently place bulk adhesive properties measured under one standard beside stone properties determined under another, often using newly quarried material that bears little resemblance to a weathered nineteenth-century monument. The more meaningful question is whether the **completed repair system** transfers forces into the historic stone in a way that creates an unnecessarily damaging failure hierarchy.

Published marble adhesive research illustrates why this distinction matters. Podany and colleagues found that conventional epoxy and polyester joints commonly exceeded the capacity of the marble specimens, but their concentrated Paraloid B-72 systems and B-72 intervention-layer assemblies also frequently failed within the marble rather than through the adhesive interface. Jorjani and colleagues reached a complementary conclusion through fracture-mechanics testing, demonstrating that several thermoplastic systems could provide viable structural performance and emphasizing interfacial fracture toughness and bond-line width rather than treating nominal adhesive strength as the only useful measure. Together, these studies undermine the assumption that choosing a conventionally “weak” or reversible resin guarantees that the repaired joint will surrender before the stone.

The implications extend beyond material selection. If both thermoplastic and thermosetting systems can exceed the cohesive capacity of marble under some conditions, conservation performance must be sought partly through the architecture of the repair. Bonded area can be limited. Stable bearing can be restored so that adhesive is not carrying loads more appropriately transferred through compression. Permanent restraint can be confined to locations where the surrounding marble is sound. Perimeter materials can remain maintainable. Mechanical reinforcement can be reserved for conditions in which it performs a necessary structural function rather than being introduced reflexively. Failure hierarchy, in other words, can be influenced through **system design even when no adhesive possesses an ideal sacrificial strength.**

That conclusion provides the central synthesis of Technical Paper No. 3. Structural-adhesive selection for historic marble is not fundamentally a search for the “right glue.” It is a treatment-design problem involving material behavior, structural mechanics, substrate condition, exposure, reversibility, workmanship, and future intervention.

29.2. Strength, Stiffness, Toughness, and the Limits of Single-Property Selection

The tendency to focus on tensile strength is understandable because strength is easily communicated and commonly reported by manufacturers. It also produces an appealingly simple rule: if the adhesive is stronger than the stone, the adhesive is too strong. The difficulty is that joints do not experience material properties independently. Two adhesives with different ultimate tensile strengths can transmit stress into marble very differently if their elastic moduli, fracture toughness, elongation, bond-line thickness, or adhesion differ. A lower-strength but very stiff adhesive may resist movement at relatively small displacement and concentrate stress in neighboring stone, while a stronger but somewhat more compliant system may distribute that movement differently. Neither can be classified confidently from ultimate strength alone.

Fracture toughness adds another dimension because real stone joints contain cracks, flaws, irregular surfaces, pores, and stress concentrations. Failure commonly begins at one of these discontinuities rather than when the entire adhesive layer simultaneously reaches a uniform tensile limit. Jorjani's emphasis on interfacial fracture toughness is therefore especially important to historic marble repair because it considers crack initiation and propagation at the stone-adhesive interface rather than treating the joint as an ideal homogeneous material. The importance of bond-line width in the same research reinforces the conclusion that geometry participates directly in material behavior.

Historic marble makes any single-property approach still less reliable. Weathering progressively changes grain cohesion, microcrack density, porosity, moisture behavior, and stiffness. The mechanical properties of the marble can vary not only from one monument to another but within different regions of the same stone. A newly fractured interior surface may retain good crystalline cohesion while the adjacent exterior has experienced substantial granular disintegration. An old fracture left open for decades may be weathered throughout the bond zone. The adhesive therefore does not encounter “marble” as an abstract engineering substrate; it encounters a particular volume of historic stone with a particular deterioration history.

Once adhesive capacity exceeds that local substrate capacity, further increases in adhesive strength become progressively less important. The stone becomes the limiting material. At that point, the conservation problem shifts from maximizing adhesion to controlling where the loads enter the marble and what happens when those loads exceed the stone's remaining capacity. This is why bonded surface area, edge distance, pad location, bearing, and joint geometry recur throughout the paper. They are not secondary installation details but variables controlling the amount and distribution of force transferred into original material.

The same reasoning cautions against replacing one simplistic material hierarchy with another. Thermoplastic acrylics should not be considered automatically safe because they remain soluble; mineral grouts should not be considered automatically compatible because they are inorganic; epoxy putties should not be considered automatically harmful because they are hard and permanent. Each category contains useful materials and important limitations. The treatment decision becomes defensible only when those properties are related to the actual structural function the material must perform.

29.3. Structural Bonding and Structural Support Are Not the Same Function

One of the clearest findings of this study is the importance of distinguishing **bonding from support**. This distinction is especially consequential in multi-piece monuments, where the weight of the upper component ordinarily acts downward through a broad horizontal interface. If that interface is properly configured, much of the monument's dead load can be carried through compression, bearing, and friction without requiring structural adhesive to suspend the component or convert the entire joint into a rigid laminate.

This observation alters the way large monument reassembly should be conceptualized. A broad die resting on a sound base does not necessarily present the same adhesive problem as a broken tablet. The tablet fracture interrupts structural continuity through a

relatively thin section and may require an adhesive to transmit bending, shear, and tension across the break. A properly seated monument die already possesses an independent gravitational load path. Its connection may need additional resistance to sliding, rocking, rotation, or uplift, but those demands should be quantified conceptually before the entire interface is bonded.

The Gravestone Guardians use of lead wedges, localized Pratley Standard Setting Putty, and monument setting compound is important in this context because the three materials can be understood as performing different functions. Lead assists alignment and local bearing adjustment. The stone itself remains the principal compression-bearing material. Localized putty provides supplemental restraint. Perimeter compound closes and protects the exterior joint while remaining more accessible for future maintenance. The conservation argument for the system does not require Pratley Putty to be weaker than marble. Rather, it depends upon ensuring that the putty's **structural role and bonded area are limited**.

That distinction also explains why a continuous application of the same putty would constitute a fundamentally different treatment. If broad areas of polymer become responsible for supporting vertical load, filling irregular geometry, resisting lateral movement, and sealing the exterior simultaneously, functional separation is lost. The adhesive has become both bedding system and restraint, and the conservation advantages attributed to limited bonding diminish accordingly. The same product can therefore participate in either a restrained or highly invasive repair depending upon how it is configured.

This separation of functions is not peculiar to the GG system. The broader monument-setting tradition distinguishes wedges, setting compounds, mortars, adhesives, and mechanical reinforcement precisely because they do not perform identical tasks. Technical Paper No. 3 gives that practical distinction a conservation-mechanics rationale. It proposes that treatment should begin by asking which forces can be carried through the monument's existing geometry and compatible bearing before introducing permanent structural connection.

The significance of this finding extends beyond adhesive quantity. It changes the treatment sequence. Foundation and bearing conditions must be evaluated before the adhesive is chosen. If the component rocks because the base is uneven, adhesive should not be asked to compensate for the defect. If the foundation continues to settle, rigidly connecting upper components more strongly may simply conceal relative movement until stress is transferred into the marble. The repair should address the source and path of load before increasing joint strength.

29.4. Failure Hierarchy as the Central Conservation Metric

The concept of failure hierarchy provides a more complete conservation criterion than either maximum bond strength or maximum reversibility. It asks what part of the repaired monument is expected to surrender first when the system experiences loads beyond its intended service range and what the consequence of that surrender will be.

An ideal hierarchy cannot be defined simply as adhesive failure before stone failure because premature adhesive release can itself be destructive. A large elevated fragment that separates cleanly but falls and shatters has not been preserved merely because no marble remained attached to the resin. Likewise, a low monument component bonded across its entire base may remain exceptionally secure but transfer an extraordinary lateral event into a large breakout of original marble. Neither system can be judged without considering both the load at which failure occurs and the damage produced when it does.

The desired hierarchy is therefore contextual. During normal service, the monument should remain stable with appropriate reserve capacity. Maintenance materials may deteriorate first and be renewed. When unusual movement develops, visible changes at the perimeter may provide warning before structural damage progresses. If load continues beyond the intended capacity, localized treatment-material failure or limited substrate damage may be preferable to broad cohesive fracture. In safety-critical assemblies, however, the consequences of component release can justify stronger and more invasive positive restraint.

This interpretation resolves a recurring false opposition between conservation and structural performance. Conservation does not demand fragile joints. Structural performance does not demand that every joint be made as strong as technically possible. The objective is sufficient capacity combined with an acceptable failure consequence.

Failure hierarchy also creates a useful basis for comparing pinning with adhesive repair. Pins can provide reliable positive restraint where the structural demand requires it, but drilling removes original material and transfers force through concentrated zones around the anchorage. Adhesive-only systems avoid those holes but may create broad rigid interfaces or rely too heavily on the cohesive strength of weathered surfaces. Limited bonding reduces permanent interface area but cannot substitute for a pin when substantial uplift or overturning resistance is required. The decision must therefore turn on which intervention provides the necessary structural function with the least damaging likely consequence.

This same framework should guide future experimental evaluation. A specimen that carries the highest peak load should not automatically be ranked as the best conservation repair.

Load must be considered alongside displacement, stone-loss area and depth, crack propagation, failure location, residual stability, and retreatability. The Conservation Failure Index proposed in Chapter 23 is one possible method of organizing those outcomes, but the underlying principle is more important than any particular score: **the amount of original material lost when the repair reaches its limit is itself a performance property.**

29.5. Reversibility Reconsidered

The evidence reviewed in this study strongly supports retaining reversibility as an important conservation objective while abandoning the expectation that it can function as an absolute material classification. AIC's current Guidelines for Practice require treatment materials and methods to be appropriate to the specific object and explicitly direct conservators to balance their advantages against adverse effects on future examination, investigation, treatment, and function. The same guidance recognizes nonintervention as legitimate when treatment does not best serve preservation and requires permanent documentation of interventions (American Institute for Conservation, n.d.). This framework is more nuanced than a simple prohibition on irreversible materials.

Podany's B-72 research illustrates why. Properly prepared B-72 intervention layers substantially increased the reversibility of structural joints without necessarily reducing their strength below that required for large-stone reassembly. The researchers emphasized that the barrier should be thin, continuous, conformal, and fully dried before the secondary adhesive was introduced. At the same time, many of these joints remained strong enough that the marble failed before the adhesive system (Podany et al., 2001). The intervention layer therefore improved future intentional separation without guaranteeing sacrificial mechanical failure during overload.

This distinction between **mechanical failure hierarchy and deliberate retreatability** should remain explicit. A repair can perform favorably in one dimension and poorly in another. B-72 may create a chemically weakenable interface without ensuring that the stone is protected during impact. A limited Pratley system may remain chemically irreversible yet preserve physical pathways for future dismantling because most of the interface remains unbonded. A pin may occupy a small surface footprint while becoming extremely difficult to remove because reinforcement and epoxy extend deeply into the original stone.

Technical Paper No. 3 therefore proposes a broader concept of retreatability incorporating chemical, geometric, and informational dimensions. Chemical retreatability concerns whether a material can be weakened or dissolved. Geometric retreatability concerns whether the intervention is accessible and localized enough to permit separation.

Informational retreatability concerns whether future practitioners know what material was used, where it was placed, and how the repair was constructed. A treatment becomes more conservative when these dimensions reinforce one another.

This approach does not reduce the burden associated with permanent epoxy. On the contrary, it clarifies the obligation. Where a chemically irreversible adhesive is selected, its structural necessity should be established, its extent should be limited, its location should be documented, and the future treatment implications should be acknowledged openly. Permanence is most defensible when it is proportionate rather than casual.

29.6. Material-Specific Findings

The comparative material review does not support identifying one universally preferred adhesive for historic marble, but it does permit several reasonably strong distinctions.

Akepox 5010 remains a defensible primary candidate for close-fitting tablet fractures in marble possessing adequate cohesive strength. Its suitability arises from the combination of structural capacity, controlled gel consistency, low shrinkage, weather resistance, and the ability to form comparatively thin bond lines rather than from any claim that it is inherently conservation-safe. Its limitations are equally important: the cured resin is effectively permanent in normal conservation practice, and a sufficiently strong bond can redirect later fracture into surrounding marble. The treatment should therefore remain closely matched to the fracture, with unnecessary surface spread avoided and substrate condition governing whether adhesive repair is attempted.

Pratley Standard Setting Putty occupies a different role. The evidence developed in this paper supports continued consideration of the material as a localized restraint within multi-piece monuments whose primary load is already carried through stable compression and bearing. The limited public mechanical data remain a significant research gap, and no claim should be made that Pratley is sacrificial relative to marble. Its conservation case instead rests upon controlled placement, reduced bonded area, good working properties, and avoidance of drilling where positive mechanical reinforcement is unnecessary. If the putty becomes a continuous bedding material, that argument changes materially.

Tenax Domo 10 and related fabrication epoxies demonstrate why commercial performance criteria should not be transferred automatically into conservation. A product designed to create extremely durable stone-to-stone bonds may be entirely successful in fabrication while offering no clear advantage for weathered historic marble if adequate capacity can be obtained through a less aggressively bonded system. Such products remain legitimate candidates where their particular properties solve a defined problem, but “stone-breaking”

adhesion should be regarded as a characteristic requiring conservation scrutiny rather than an unqualified benefit.

Thermoplastic acrylics, particularly Paraloid B-72 and B-48N systems, deserve more structural consideration than they often receive. Published research demonstrates that several such formulations can provide meaningful marble-bond performance (Jorjani et al., 2008). Their principal advantage is improved retreatability, while their principal concerns for exterior structural use include solvent drying, temperature-dependent mechanical behavior, creep, formulation variability, and incomplete evidence under cemetery conditions. They are therefore strong research and specialized-treatment candidates rather than proven wholesale replacements for exterior structural epoxy.

Intervention layers represent one of the most promising lines for future study because they attempt to preserve thermoset structural capacity while isolating the permanent adhesive from direct contact with historic stone. Existing research establishes the concept as technically credible in marble sculpture (Podany et al., 2001). What remains uncertain is long-term performance on weathered exterior marble, including moisture transport, repeated environmental cycling, solvent retention, and practical retreatability in large cemetery joints.

Mineral grouts and mortars perform important roles but should not be treated as “safer glue.” Their conservation advantages are strongest when their function matches their material behavior: injection into suitable cracks and voids, distributed mineral consolidation, bedding, loss compensation, or sacrificial pointing. A high-performance cementitious grout can itself be strong and stiff; mineral composition does not guarantee that failure will occur within the repair rather than the marble. The distinction between grout and fracture adhesive should therefore remain explicit.

Conventional polyester mastics appear to offer relatively little advantage for routine exposed historic marble where exterior structural epoxies or appropriate mineral materials are available. Rapid cure, ease of coloring, and fabrication familiarity remain useful properties, but shrinkage, environmental limitations, UV behavior, and permanence make them less compelling for the applications emphasized in this paper. Existing stable polyester repairs should not, however, be removed solely because a different product would now be selected. Their actual condition and effect on the stone remain the appropriate basis for treatment.

29.7. The Gravestone Guardians Limited-Bond Hypothesis

The Gravestone Guardians limited-bond approach emerges from this review as neither established conservation doctrine nor an unsupported field improvisation. Its individual

components—stable bearing, lead wedges, structural adhesive, and maintainable setting materials—have recognizable antecedents in monument setting and preservation practice. The originality lies more in formalizing their relationship as a deliberate conservation system and proposing that bonded area and functional separation should be treated as design variables.

The hypothesis is mechanically coherent. If a large stone component is already supported through gravity and stable bearing, an adhesive need not carry the same structural responsibilities required of a tablet fracture bond. Limiting permanent restraint to selected locations reduces the amount of original interface committed to irreversible polymer and may limit the total force transferred through the adhesive during extreme movement. Keeping the perimeter independently maintainable preserves access, while avoiding unnecessary drilling retains original stone that would otherwise be removed for reinforcement.

The hypothesis remains incompletely validated. Localized adhesive can create stress concentrations. Pad placement and area influence the result. Lead can creep. Foundation movement can alter the load path until adhesive begins carrying forces it was never intended to resist. Pratley's relevant mechanical properties are not sufficiently documented publicly to substitute manufacturer claims for independent testing. A low monument and a tall slender monument cannot be assumed to respond similarly simply because both contain horizontal joints.

For these reasons, the strongest conclusion available today is conditional: **limited-bond reassembly is a reasonable conservation candidate for selected broad, inherently stable monument assemblies, but its performance boundaries should be established through controlled testing and systematic field monitoring before it is promoted as a general standard.** This is a stronger position than either immediate endorsement or rejection because it specifies the mechanical circumstances under which the method makes sense and identifies the evidence still required.

29.8. From Product Selection to Conservation Engineering

Taken together, the findings of this study point toward a more mature way of discussing structural adhesives in historic stone conservation. The choice does not need to be framed as traditional conservators opposing modern monument setters, nor as reversibility competing with structural competence. Both perspectives identify legitimate risks. Conservation brings necessary caution about permanence, substrate damage, future treatment, and the irreversible consequences of excessive strength. Monument-setting

practice brings necessary experience with gravity, bearing, field durability, practical assembly, and the requirement that heavy stone remain stable outdoors.

The more useful synthesis is a form of conservation engineering in which the monument is treated as a coupled system. Material properties are considered alongside load path, weathering, geometry, bearing, environmental exposure, workmanship, maintenance, and eventual failure. The objective is neither to reproduce commercial fabrication practice unchanged nor to impose museum-object adhesive doctrine on cemetery structures without adjustment.

This approach also places uncertainty where it belongs. Some treatment decisions can be supported confidently by existing research; others remain provisional. A conservation organization should not conceal those differences. A method supported principally by field experience should be described that way. A laboratory result obtained on sound Carrara marble should not be presented as proven performance on weathered New England gravestones. A manufacturer specification should not be treated as independent conservation research. Conversely, the absence of a perfect study should not prevent reasonable, documented, minimally invasive treatment when a monument requires stabilization.

The final measure of the approach is therefore not ideological purity. It is whether the selected intervention provides adequate stability while preserving as much original material, future information, and future treatment flexibility as the structural problem reasonably permits.

30. Principles for Structural Adhesive Repair

30.1. Purpose of the Principles

The preceding chapters provide a detailed analytical basis for treatment selection, but field practice also benefits from a concise set of principles capable of guiding decisions across different monument configurations. These principles are not intended as product instructions or substitute engineering specifications. They summarize the conservation philosophy developed through this paper and establish the reasoning that should precede product selection.

Their order is intentional. The first questions concern necessity, stone condition, and structural function. Adhesive choice appears only after those conditions are understood. The purpose is to prevent the material already on the truck, the method used on the previous monument, or an assumption about what constitutes a “professional repair” from determining the treatment prematurely.

1. Use the least invasive system that provides adequate stability.

Minimum intervention applies only among treatments capable of fulfilling the preservation requirement. An inadequately restrained monument is not made conservative by using less material if ordinary service can cause renewed movement or collapse. Conversely, additional bonding, drilling, or reinforcement should not be introduced merely because it increases ultimate capacity. The appropriate treatment is the least invasive configuration that can reasonably resist the loads the monument is expected to encounter with an appropriate margin for uncertainty.

This principle deliberately couples **least invasive** with **adequate**. Either phrase without the other can lead to poor treatment. Adequacy prevents under-treatment; minimum intervention prevents unnecessary structural escalation.

2. Assess the stone before designing the repair.

Historic marble is not a standardized substrate. Weathering, grain structure, microcracking, salts, moisture, previous repair, and fracture history can reduce or localize its capacity significantly. Adhesive selection should therefore follow examination of the actual load-transfer zone rather than the monument's general classification as marble.

A product suitable for a close fracture through sound crystalline material may be inappropriate several inches away where the same monument is severely sugared. Where the stone lacks sufficient cohesion to receive the intended load, stronger adhesive is not the solution. The structural concept must change.

3. Diagnose the cause of failure before increasing joint strength.

A separated joint may be the symptom rather than the cause of monument instability. Settlement, frost movement, drainage, corrosion, poor bearing, impact, vegetation, and earlier repairs can all create displacement. Reassembling the components more rigidly without addressing an active mechanism can redirect the same movement into previously intact stone.

Foundation condition and bearing should consequently be investigated before structural adhesive or reinforcement is introduced. A joint should not be strengthened merely to prevent the monument from visibly expressing a problem that remains active elsewhere.

4. Separate bearing, restraint, bonding, filling, and weather protection whenever practical.

No single repair material should be expected automatically to support weight, correct alignment, bond fragments, fill losses, resist overturning, and seal the exterior. These are different functions with different material requirements.

In multi-piece monuments, gravity and sound bearing should carry dead load wherever geometry permits. Lead or other appropriate shims can refine bearing and alignment. Adhesive may supply supplemental restraint. Mineral repair materials may replace missing volume. Setting compound, lime mortar, or historically appropriate joint material can manage the perimeter. Functional separation reduces the likelihood that one highly permanent material becomes unnecessarily dominant throughout the assembly.

5. Use adhesive strength as a threshold, not as the treatment objective.

A structural adhesive must possess sufficient capacity for its intended role. Once that requirement and appropriate reserve capacity have been satisfied, additional bond strength should be evaluated according to what it contributes to preservation. If greater strength merely increases the load transferred into weathered marble during an extreme event, it may offer little conservation benefit.

This principle is especially important when evaluating commercial claims that a bond is stronger than the stone. Such performance can be desirable in fabrication and may occasionally be necessary in conservation, but it should not be confused with the objective of historic-material preservation. The relevant question is not how difficult the joint is to break, but whether it remains reliably stable in service and what is lost if it eventually does break.

6. Design the repair around a deliberate failure hierarchy.

Every structural system has a limit. Conservation should consider that limit before treatment rather than only after failure. The practitioner should identify what is expected to happen as load increases: whether friction is overcome, perimeter material cracks, adhesive engages, a pad releases, a pin transfers load, or marble begins to fracture.

The preferable hierarchy maintains stability throughout expected service while directing extraordinary damage toward replaceable or localized treatment components where practical. The hierarchy must also account for safety. A joint that releases harmlessly from the stone but permits a heavy component to fall is not a successful sacrificial repair. Adequate service capacity and acceptable failure consequence are inseparable parts of the same design problem.

7. Limit permanent bonded area when broader bonding provides no structural benefit.

The extent of the adhesive interface is a conservation variable. Full-surface bonding should therefore require the same justification as any other enlargement of an irreversible treatment. Where a close fracture requires continuous adhesive contact across its existing break, broad wetting is structurally appropriate. Where a large horizontal interface is already independently stable, permanent bonding need not automatically cover every available square inch.

Limited bonding is not synonymous with weak or incomplete application. Within each intended bond region, adhesion should be reliable. The conservation restraint lies in defining how much of the historic interface genuinely needs permanent structural connection.

8. Preserve future treatment options through chemistry, geometry, and documentation.

Reversibility should be pursued where practical, but its effectiveness must be assessed at the treatment level rather than by resin category alone. Thermoplastic adhesives and intervention layers can provide valuable chemical retreatability. Localized permanent bonding can provide geometric retreatability by preserving physical access. Detailed records create informational retreatability by allowing future practitioners to know where and how the intervention was made.

These strategies should be combined where useful. A chemically irreversible material used sparingly and documented accurately may preserve more practical future options than the same material applied continuously. A soluble adhesive hidden deeply inside an

inaccessible joint may be less readily reversed than its chemistry suggests. Future treatment should be considered before the present joint is closed.

9. Use pinning when structural demand requires positive mechanical reinforcement, not as a default sign of workmanship.

Pins, dowels, and anchors remain essential tools in historic-stone conservation. Tall, slender, projecting, elevated, or safety-critical components can require positive mechanical restraint that adhesive, bearing, or friction alone cannot provide responsibly. In such cases drilling may represent necessary permanence.

The same intervention becomes difficult to justify when a low, broad monument is already inherently stable and requires only modest supplemental restraint. Drilling removes original stone and establishes concentrated load-transfer zones; it should therefore solve a clearly identified structural problem. The absence of a pin does not make a repair incomplete, just as the presence of a pin does not make a repair inherently professional.

10. Treat documentation and monitoring as components of the structural repair.

The long-term conservation value of a repair depends partly upon whether future practitioners can understand what was done and observe how it performs. Adhesive locations, pin dimensions, bearing materials, intervention layers, perimeter compounds, foundation work, and substrate condition should therefore be recorded while they remain visible.

Monitoring should examine the entire monument rather than simply determining whether an adhesive seam remains intact. Changes in foundation, bearing, joint width, edge cracking, lead position, moisture, perimeter material, or adjacent marble can reveal changes in the load path long before catastrophic failure occurs. A durable repair is strengthened by a record that makes future retreatment more informed and by inspection capable of identifying deterioration before another major intervention becomes necessary.

30.2. Applying the Principles Together

These principles are most useful when applied as a connected sequence rather than isolated rules. Minimum intervention cannot be determined without understanding the structural demand. Structural demand cannot be understood without examining the monument and diagnosing why it failed. Material selection cannot be separated from joint geometry. Failure hierarchy cannot be defined without considering the consequences of component release. Retreatability cannot be evaluated without knowing how much of the interface is permanently altered and whether future access will exist.

This interconnectedness explains why a universal adhesive rule is unlikely to serve historic marble well. Two visually similar monuments may require different treatments because one possesses sound bearing while the other does not, one contains strong interior marble while the other is deeply sugared, or one is a low die while the other places a heavy elevated element above public access. The same conservator can therefore choose direct epoxy, limited-bond restraint, mineral setting, or mechanical reinforcement in different situations without inconsistency. The consistency lies in the reasoning used to reach the decision.

These principles should likewise prevent the Gravestone Guardians limited-bond approach from hardening into doctrine. The method is valuable only where the monument satisfies its underlying assumptions. If stable bearing cannot be established, if restraint demands are high, if the substrate cannot receive localized bonding, or if component release presents unacceptable consequences, another treatment should be selected. Minimum intervention is not loyalty to the least invasive technique used previously; it is willingness to use no more intervention than the present monument actually requires.

The resulting philosophy is intentionally conservative in both senses of the word. It resists unnecessary alteration of original material while also resisting unnecessary certainty about materials and methods whose long-term performance remains incompletely studied. Treatment can proceed responsibly under uncertainty when the assumptions are explicit, the intervention is proportionate, and the outcome is monitored.

31. Conclusions and Recommendations

31.1. The False Choice Between Strong and Weak Repair

Structural adhesive repair of historic marble has often been discussed through a binary framework. On one side stands the modern structural adhesive: strong, durable, resistant to moisture, and difficult to reverse. On the other stands the traditional conservation preference for weaker, more compatible, or more reversible materials intended to protect original stone from being made sacrificial to the repair. Each position contains an important truth, but neither provides an adequate treatment rule by itself.

High-strength adhesives can indeed redirect failure into original marble. The conservation concern is supported both mechanically and experimentally. Yet weaker or more reversible adhesives do not guarantee that failure will occur harmlessly at the joint. Podany's marble testing demonstrated cohesive stone failure across epoxy, polyester, concentrated B-72, and B-72 barrier systems under many of the tested configurations (Podany et al., 2001). Jorjani's later fracture-mechanics work likewise showed that several thermoplastic systems could provide viable structural performance, reinforcing the conclusion that adhesive category alone does not establish failure behavior (Jorjani et al., 2008).

The evidence therefore supports a more useful proposition: the conservation suitability of an adhesive emerges from the relationship among the adhesive, the historic substrate, and the structural configuration in which the two are joined. Strength is necessary but incomplete. Stiffness, fracture toughness, bond-line thickness, bonded area, penetration, environmental exposure, creep, joint geometry, stone condition, workmanship, and retreatability all participate in the result.

The fundamental treatment question should consequently change from **“Is this adhesive stronger than marble?”** to **“What structural role is this material performing, how much capacity is required, and what will happen to the historic stone when the completed system is loaded, aged, or eventually retreated?”**

That is the principal conclusion of Technical Paper No. 3.

31.2. Implications for Structural Epoxy

The study does not support categorical rejection of thermosetting structural epoxy in historic marble conservation. There are repair conditions in which a durable, low-shrinkage, weather-resistant structural adhesive provides an appropriate means of restoring continuity while avoiding other irreversible interventions such as drilling. Closely fitting tablet fractures represent the clearest example. Where the marble adjacent to the

break remains sufficiently cohesive, a controlled thin epoxy bond can re-establish structural continuity across an existing fracture without removing additional original material for reinforcement.

Such use must nevertheless be described without understating its permanence. Once cured, structural epoxy is not practically reversible in the manner of a thermoplastic acrylic. The fracture surfaces become permanently altered to some degree, and future severe loading may produce fracture in neighboring marble rather than release of the original joint. These characteristics create a responsibility to restrict the treatment to sound substrate, minimize unnecessary adhesive spread, document the intervention, and monitor the repaired stone over time.

Within that framework, Gravestone Guardians' continued use of AKEPOX 5010 as a primary candidate for appropriate tablet breaks remains technically defensible. The conclusion should not be converted into a blanket product endorsement. The product is suitable because its material characteristics and working properties correspond reasonably to a defined repair geometry, not because one epoxy has been established as universally superior to every alternative.

Alternative structural epoxies, conservation epoxies, and thermoplastics remain legitimate options where their specific characteristics address a particular treatment need. Tenax Domo 10 may provide exceptional permanent adhesion but offers no obvious conservation advantage merely because it produces a stronger fabrication bond. HXTAL and Epo-Tek systems possess important conservation and research histories but introduce different viscosity, cure, and exterior-service considerations. Paraloid systems offer substantially greater retreatability while raising unresolved questions about solvent drying, creep, temperature-dependent behavior, and long-term cemetery exposure.

The appropriate organizational practice is therefore to maintain a **small, evidence-based family of materials assigned to specific functions** rather than searching continually for a single adhesive capable of replacing all others.

31.3. Implications for Multi-Piece Monument Reassembly

The conclusions are more consequential for broad horizontal monument joints because these assemblies frequently do not require adhesive to carry the primary dead load. Gravity, bearing, friction, and monument geometry already provide much of their normal structural stability.

This observation creates a conservation opportunity. Where stable bearing can be restored and the component's geometry does not require positive mechanical anchorage,

permanent adhesive can potentially be confined to the amount needed for supplemental restraint rather than being spread continuously across the historic interface. Lead wedges or other appropriate bearing materials can establish alignment and distribute contact; localized structural adhesive can resist sliding or opening; and a maintainable perimeter material can manage environmental exposure. The resulting assembly remains structurally connected without attempting to transform every interface into a monolithic permanent bond.

The Gravestone Guardians use of localized Pratley Standard Setting Putty within this type of system is therefore best understood as a **limited-bond reassembly hypothesis**, not as an assertion that Pratley possesses ideal conservation strength. Its potential advantage lies in controlling bonded area and separating structural functions. The same material used as a large continuous bedding layer would no longer embody the same treatment logic.

This distinction should become central to future GG practice. A limited-bond monument should remain stable in bearing before adhesive cure. The adhesive should supplement the load path rather than create it. Pad locations should be deliberate and documented. Fragile edges and weak marble should be avoided. The perimeter should remain independently maintainable. If the amount of adhesive required expands substantially because the stone cannot be seated stably, the treatment has crossed into another structural category and should be reconsidered accordingly.

Existing practice provides reason to take this combined approach seriously, but direct experimental validation is still needed. The method should therefore remain a provisional GG standard for appropriate monument configurations accompanied by documentation and monitoring, while the research program proposed in this paper establishes its actual performance boundaries.

31.4. Implications for Pinning

Technical Papers No. 2 and No. 3 together reject the idea that pinning represents an automatic improvement over adhesive repair. Mechanical reinforcement is neither inherently more conservative nor inherently more destructive. It performs a structural function that should be introduced when that function is necessary.

Pins and dowels provide positive resistance to separation and movement that may be essential for tall, narrow, elevated, projecting, or safety-critical stone components. In those conditions, reluctance to drill can become as problematic as indiscriminate pinning. A weak or limited adhesive system is not a conservation success if predictable loading can cause a dangerous component to release.

At the same time, drilling permanently removes historic material and introduces concentrated load transfer into the remaining stone. Where a broad monument component already possesses substantial stability through mass and bearing, new dowels introduced primarily as insurance may represent unnecessary intervention. The comparison should therefore be made between the consequences of two adequate systems rather than between an adhesive joint imagined as weak and a pin imagined as secure.

The appropriate decision sequence is increasingly clear. First determine the inherent stability of the assembly. If bearing and geometry provide sufficient stability, no additional structural connection may be required. If modest restraint is needed, limited bonding can be considered. If the joint itself must transmit substantial structural load, continuous adhesive may be justified. If positive mechanical reinforcement is required to control uplift, bending, overturning, or hazardous release, pinning becomes appropriate. The progression is not rigid; it is a way to prevent the most invasive option from being selected before the actual demand has been established.

31.5. Reversibility, Retreatability, and the Reality of Structural Conservation

Structural monument repair demonstrates why reversibility is better understood as a spectrum of future treatment options than as an absolute material property. AIC's current professional guidance reflects this broader approach by emphasizing treatment suitability, preservation of future examination and treatment, documentation, and the recognition that nonintervention may sometimes be appropriate (American Institute for Conservation, n.d.).

This paper therefore recommends that structural treatments be evaluated through three related forms of retreatability. Chemical retreatability considers whether an adhesive can be dissolved or weakened. Geometric retreatability considers whether the intervention remains accessible and sufficiently localized for future separation. Informational retreatability considers whether documentation enables another practitioner to understand where and how the repair was made.

The intervention-layer research of Podany and colleagues provides a particularly useful example of chemical retreatability engineered into an otherwise strong structural joint. Thin, continuous, fully dried B-72 layers beneath epoxy or polyester materially improved reversibility while retaining sufficient strength for the types of large-stone bonds investigated (Podany et al., 2001). That concept deserves further study in cemetery marble, particularly beneath Akepox 5010 tablet repairs and localized Pratley restraint. It should not yet be adopted automatically because long-term exterior moisture behavior,

environmental aging, solvent retention, and real-world dismantling remain inadequately characterized.

Geometric retreatability is already central to the limited-bond model. Leaving much of a broad monument interface unbonded can preserve physical access even where the localized adhesive itself is permanent. Documentation then completes the system by identifying the locations that future practitioners will eventually encounter.

This approach accepts that some structural conservation is necessarily permanent while refusing to treat permanence casually. Where irreversible material must be introduced, the goal should be to make the intervention **necessary, localized, legible, and retreatable to the greatest practical extent.**

31.6. Mineral Materials Should Be Used for the Work They Do Best

The investigation of mineral grouts and mortars leads to a similar conclusion. Mineral composition is an important compatibility consideration, particularly where moisture transport, thermal behavior, porosity, or traditional masonry construction is concerned. It does not automatically make a material an appropriate substitute for structural adhesive.

Injection grouts such as IG10 are most convincingly employed where their geometry and material behavior correspond to the defect: internal voids, appropriate cracks, distributed separations, and masonry conditions in which mineral reconnection is beneficial. Lime-based hydraulic grouts can provide valuable options for delamination and compatible void filling. Lime mortars and repair mortars remain useful for bedding, pointing, and loss compensation where a high-tensile structural bond is unnecessary.

A narrow tablet fracture expected to recover bending continuity poses a different requirement. Replacing epoxy with mineral grout simply because grout appears more traditional or breathable does not resolve the mechanical problem. A sufficiently strong grout may still transfer failure into marble; a weak grout may provide inadequate tensile performance. Product class cannot replace structural analysis.

The most conservation-compatible strategy is frequently mixed rather than doctrinaire. Structural adhesive can join a fracture while mineral repair mortar replaces missing edge material. Mineral bedding can distribute compression while localized polymer provides restraint. Injection grout can address internal voids without coating an entire horizontal interface with resin. Each material should be placed where its strengths correspond to the actual function.

31.7. The Need for Experimental Validation

The most important limitation of the present paper is also one of its principal conclusions: too much of the debate surrounding structural adhesives in historic marble rests upon extrapolation.

Manufacturer testing commonly measures properties optimized for fabrication or construction. Conservation research has produced valuable marble-specific comparisons, but most studies use comparatively sound specimens and controlled laboratory geometry. Cemetery monuments introduce naturally weathered substrate, decades of microcracking, moisture and salt exposure, freeze-thaw cycling, irregular fractures, large masses, bearing, friction, prior repairs, and repeated environmental movement.

Technical Paper No. 3 therefore recommends that future work shift deliberately from product comparison toward **system comparison**. The experimental program proposed in Chapters 21–24 should test direct Akepox bonds, thermoplastic systems, intervention layers, localized Pratley configurations, continuous bonding, mineral grout where geometrically appropriate, and mechanical reinforcement within standardized but conservation-relevant substrates and mock monument assemblies.

The success criterion should not be maximum load alone. The research should identify service capacity, stiffness, displacement, creep, failure location, original stone loss, fracture propagation, environmental durability, moisture behavior, and retreatability. Naturally weathered sacrificial marble should supplement sound reference stone so that substrate deterioration is treated as an experimental variable rather than an inconvenience.

Particular priority should be given to the direct questions arising from current GG practice: whether limited adhesive area materially reduces stone loss during overload; how much restraint is required beyond gravity and friction in representative multi-piece monument geometries; whether Pratley pad location affects edge breakout; whether B-72 intervention layers improve retreatability beneath AKEPOX and Pratley without compromising exterior performance; and how these systems change after sustained environmental cycling.

A research program capable of showing that a current GG practice performs poorly would be more valuable than one designed merely to validate it. The purpose of technical publication is not to make existing methods appear correct. It is to identify the conditions under which they are correct and the conditions under which another method should be chosen.

31.8. Recommended Direction for Gravestone Guardians

The immediate practical recommendation arising from this study is not a wholesale change in Gravestone Guardians materials. It is a refinement in how those materials are selected, described, documented, and evaluated.

Akepox 5010 can remain the principal candidate for appropriate close-fitting marble tablet fractures, with treatment conditioned upon substrate integrity and careful control of the bond footprint. Pinning should be considered where the expected loads, geometry, or safety consequences require reinforcement rather than being added automatically to every tablet repair.

Pratley Standard Setting Putty can remain a candidate for localized restraint in suitable compression-loaded multi-piece monuments, but the method should be explicitly defined as limited-bond reassembly. The monument must possess independent stable bearing, and the quantity of putty should not be allowed to expand until it becomes the bedding system. Lead should continue to serve as controlled bearing and alignment material rather than isolated primary support, and perimeter setting materials should remain independently maintainable.

Mineral grouts, lime mortars, and repair mortars should be incorporated according to the roles for which they are best suited rather than treated as competitors that must replace structural adhesive everywhere. B-72 and related thermoplastic or intervention-layer systems should receive increased experimental attention because they offer potentially meaningful improvements in retreatability without necessarily sacrificing the structural capacity traditionally assumed to require thermosetting resin.

Most significantly, structural repairs should be classified by the **level of intervention actually required** rather than by a preferred product. Some monuments need only bearing and joint treatment. Others benefit from limited restraint. Some fractures require a structural adhesive bond. A smaller subset requires mechanical reinforcement. Severely deteriorated monuments may require support, stabilization, or non-reassembly rather than increasingly aggressive intervention.

This hierarchy gives Gravestone Guardians a coherent treatment philosophy without turning any one technique into doctrine.

31.9. Closing Conclusion

Historic marble monument conservation exists within an unavoidable tension. The stone must be preserved, but it must also continue to function physically. A broken tablet cannot be protected by reversibility alone if it lacks sufficient continuity to stand safely. A large

monument cannot be made more conservative merely by making every joint extremely strong. A pin cannot protect historic marble if the surrounding stone is too weak to transfer its load, and an adhesive cannot compensate indefinitely for unstable bearing or a failing foundation. The solution is not to choose between conservation and structural performance. The solution is to treat structural performance as part of conservation.

That requires abandoning the assumption that a single material property can decide the repair. Tensile strength matters, but so do stiffness and fracture toughness. Adhesive chemistry matters, but so do bonded area and joint geometry. Reversibility matters, but so do accessibility and documentation. Durability matters, but so does what happens when durability finally reaches its limit. Historic compatibility cannot be judged solely by whether a material is mineral, polymeric, traditional, modern, weak, or strong.

The appropriate repair is instead the result of a series of relationships: between the strength of the adhesive and the cohesion of the stone; between the stiffness of the treatment and the movement of the monument; between the area of permanent bonding and the restraint actually required; between present stability and future retreatability; and between the consequences of treatment and the consequences of doing nothing.

Within that framework, the traditional conservation warning against excessively strong adhesives retains an important place, but its meaning becomes more precise. The goal is not to make every adhesive weaker than every piece of historic marble. Such a requirement is neither reliably measurable in the field nor sufficient to guarantee favorable failure. The goal is to avoid making original historic stone **unnecessarily sacrificial to the repair**.

For Gravestone Guardians, that principle supports a deliberately moderate position. Structural epoxy can be appropriate when a fracture genuinely requires structural bonding. Permanent putty can be appropriate when its role and area are deliberately constrained within an independently supported assembly. Mechanical reinforcement can be appropriate when positive restraint is necessary. Mineral materials can be appropriate where their physical behavior and structural function align with the defect. Reversible and intervention-layer systems should be pursued where they provide real future-treatment advantages without compromising required stability.

No one of these conclusions produces a universal recipe, and that is precisely the point. Historic monuments differ too greatly in material condition, construction, environment, significance, and structural demand for responsible conservation to be reduced to a rule that every break should be pinned, every joint epoxied, or every polymer avoided.

The more durable principle is one capable of surviving changes in products and techniques:

Understand how the monument carries load. Preserve sound original material. Correct the cause of instability before strengthening its symptoms. Use no more permanent intervention than the structural requirement demands. Design the repair around the least damaging credible failure hierarchy. Document what cannot be reversed. Monitor what cannot be predicted. And when the evidence demonstrates that a different method preserves more historic stone, change the method.

That standard does not ask conservation repairs to last forever; it asks each intervention to give the monument the greatest reasonable opportunity to survive until the next generation is entrusted with its care.

Appendix A: Adhesive and Repair-Material Property Comparison Matrix

A.1 Purpose and Limitations

This appendix consolidates the principal material systems discussed in Technical Paper No. 3 into a comparative reference. The table is intended to assist treatment analysis, not to rank products numerically from best to worst.

Manufacturer-reported values are included where sufficiently documented, but direct numerical comparison should be approached cautiously. Different manufacturers use different test methods, specimen geometries, cure schedules, substrates, and reporting conventions. Bulk tensile strength, lap-shear strength, bond strength, flexural strength, peel resistance, and fracture toughness are not interchangeable properties. Manufacturer-reported product data are consolidated with source attribution in Appendix J.

Values reported for newly manufactured adhesives or grouts should not be interpreted as predicted strength when bonded to weathered historic marble. Once adhesive or interfacial capacity exceeds the cohesive strength of the receiving stone, the marble itself becomes the mechanically limiting component.

Product formulations and technical specifications may change. Current manufacturer documentation should always be consulted before treatment.

A.2 Comparative Matrix

Table A.1: Adhesive and Repair-Material Property Comparison Matrix

Material / System	Material Type	Principal Intended Role	Selected Reported Properties	Exterior / Moisture Considerations	Retreatability	Principal Conservation Strengths	Principal Conservation Limitations	Preliminary TP3 Classification
Akepox 5010	Two-part epoxy; gel-like	Thin structural fracture bonding	Tensile strength approximately 30–40 MPa; flexural strength approximately 60–70 MPa; very low shrinkage; Shore D approximately 83 after full cure	Weather resistant; manufacturer reports adhesion to slightly humid stone; comparatively low yellowing	Low; cured material cannot normally be solvent-dissolved	Controlled viscosity; thin joints; low shrinkage; good exterior performance; useful working time	Permanent; capable of exceeding cohesive strength of weathered marble; resin penetration and adjacent fracture remain concerns	Preferred candidate for sound, close-fitting tablet fractures
Pratley Standard Setting Putty	Two-part epoxy putty	Localized restraint; three-dimensional adhesive pad; gap accommodation	Manufacturer describes high adhesive strength, hard cure, abrasion resistance; full quantitative tensile modulus/fracture-toughness data not publicly established in reviewed documents	Sets in wet conditions and underwater; exterior field use common	Low chemically; potentially moderate geometrically if used in discrete accessible pads	Mouldable; remains where placed; approximately 50-minute gel time; accommodates irregular interfaces; allows discrete application	Permanent; hard cured mass; limited published conservation-mechanical data; can become overused as bedding	Preferred candidate for limited restraint where independent bearing exists
Tenax Domo 10	Two-part thixotropic epoxy	Commercial stone fabrication and structural bonding	Current technical sheet reports Shore D approximately 62 under stated cure; manufacturer emphasizes very high adhesion; current sheet does not provide directly comparable marble tensile value	Exterior rated; damp/wet-surface capability; current TDS reports high yellowing under listed simulated outdoor exposure	Low	Strong permanent bond; broad substrate compatibility; exterior capability	Fabrication-oriented maximum-bond philosophy; yellowing concern on white marble; no demonstrated conservation advantage over 5010 for routine GG work	Acceptable with limitations / comparative research material

A.2 Comparative Matrix

Table A.1: Adhesive and Repair-Material Property Comparison Matrix

Material / System	Material Type	Principal Intended Role	Selected Reported Properties	Exterior / Moisture Considerations	Retreatability	Principal Conservation Strengths	Principal Conservation Limitations	Preliminary TP3 Classification
Tenax Elix	Clear knife-grade epoxy	Clear stone bonding	Low shrinkage; low-yellowing formulation; rapid cure relative to some conservation epoxies	Interior/exterior use	Low	Clear appearance; controllable knife-grade consistency	Permanent; limited conservation-specific weathered-marble research	Specialized alternative
HXTAL NYL-1	Low-viscosity conservation epoxy	Clear conservation bonding	Tensile strength approximately 37 MPa; tensile modulus approximately 2.18 GPa; elongation approximately 3%; flexural strength approximately 70 MPa; flexural modulus approximately 2.5 GPa	Excellent optical aging reputation; exterior structural-monument evidence limited; relatively low published heat-distortion temperature	Low	Conservation pedigree; optical clarity; comparatively well-characterized mechanical properties	Very slow cure; low viscosity may penetrate weathered marble; thermoset permanence; exterior temperature questions	Specialized / research benchmark
Epo-Tek 301-2	Low-viscosity optical epoxy	Specialized structural/optical bonding	Manufacturer reports long pot life; high lap shear under specified conditions; storage modulus in approximately 3 GPa range under reported conditions	Not formulated specifically as cemetery stone adhesive	Low	Included in conservation marble research; excellent wetting; long working time	Permanent; low viscosity; cure requirements and field practicality less favorable for routine monument repair	Specialized / research benchmark
Akepox 2000	Low-viscosity structural epoxy	Fluid stone bonding	Very low curing shrinkage; exterior and slightly damp-stone capability	Weather resistant	Low	Conservation research precedent; excellent penetration and wetting	Greater flow and penetration than 5010; difficult control on vertical fractures	Specialized / research benchmark

A.2 Comparative Matrix

Table A.1: Adhesive and Repair-Material Property Comparison Matrix

Material / System	Material Type	Principal Intended Role	Selected Reported Properties	Exterior / Moisture Considerations	Retreatability	Principal Conservation Strengths	Principal Conservation Limitations	Preliminary TP3 Classification
Paraloid B-72	Thermoplastic acrylic	Reversible adhesive; intervention layer; coating/consolidant	Mechanical behavior strongly dependent on concentration, solvent, bond width, drying; dry Tg generally around 39–40°C	Excellent conservation-aging reputation; exterior structural-load behavior less established	High relative to thermosets, but geometry dependent	Solvent-responsive; excellent conservation history; can provide substantial marble-bond capacity	Solvent retention; creep near elevated temperatures; formulation variability; penetration into weathered stone; difficult reversal in inaccessible joints	Specialized / high-priority research candidate
Paraloid B-48N	Thermoplastic acrylic	Adhesive / coating; potential blend with B-72	Greater toughness/flexibility characteristics than some acrylics; conservation marble research exists	Exterior coating properties favorable; structural cemetery evidence limited	High relative to thermosets	Potential to modify thermoplastic joint behavior while retaining solubility	Limited field evidence for structural historic marble	Experimental candidate
B-72 + structural epoxy intervention system	Layered thermoplastic/thermoset system	Structural bond with retreatable barrier	Podany research demonstrates substantial structural capacity and improved solvent-assisted separation	Exterior moisture transport and long-term field behavior require further study	Moderate to high relative to direct epoxy if layer remains accessible and intact	Limits direct thermoset contact and penetration; greatly improves deliberate separation in published marble tests	Barrier continuity, solvent retention, moisture transport, field application complexity; does not guarantee sacrificial overload failure	High-priority research candidate
B-72 + Pratley intervention system	Layered thermoplastic/epoxy-putty system	Localized retreatable restraint	No direct published weathered-marble validation identified	Exterior behavior unknown	Potentially moderate-high	Combines geometric and chemical retreatability conceptually	Unvalidated; B-72 may become weakest load interface; solvent drying beneath thick putty uncertain	Experimental only

A.2 Comparative Matrix

Table A.1: Adhesive and Repair-Material Property Comparison Matrix

Material / System	Material Type	Principal Intended Role	Selected Reported Properties	Exterior / Moisture Considerations	Retreatability	Principal Conservation Strengths	Principal Conservation Limitations	Preliminary TP3 Classification
Conventional polyester mastic / Marmorkitt-type systems	Polyester resin mastic	Fabrication seam filling, bonding, patching	Fast cure; strong adhesion; shrinkage greater than many epoxies	Many conventional products are interior rated or have limited UV stability	Low	Fast cure; tintable; polishable; extensive fabrication history	Shrinkage; brittle cure; yellowing/UV limitations; permanence; little advantage for exposed historic marble	Generally avoid for routine exterior historic marble
IG10 Injection Grout	Cementitious mineral injection grout	Crack/void injection; distributed mineral reconnection	Manufacturer reports approximately 7,300 psi compressive strength, 1,815 psi bond strength, 1,700 psi flexural strength, elastic modulus approximately 2,350 ksi; porosity approximately 6%	Mineral, porous, hydraulic cure; no synthetic polymer binder	Moderate to low depending on depth and geometry	Compatible mineral character; crack/void filling; measurable permeability; low-shrink formulation	Strong and comparatively stiff; not automatically sacrificial; less suited to very thin tensile fracture joints; deep injection may be effectively irreversible	Preferred for appropriate voids/cracks; specialized for complete fracture rejoining
NHL / lime-pozzolan injection grout	Mineral hydraulic grout	Delamination and void filling	Formulation dependent	Generally compatible with traditional masonry; requires controlled cure	Moderate	Adjustable strength/porosity; mineral compatibility	Shrinkage, slower strength development, injectability and formulation sensitivity	Preferred where distributed mineral grouting is appropriate
Lime bedding mortar	Mineral mortar	Distributed compressive bearing	Formulation dependent	Good vapor/moisture compatibility when properly formulated	Generally favorable	Sacrificial; replaceable; distributes support	Low tensile restraint; inappropriate as substitute for required structural connection	Preferred where bedding—not structural bonding—is required
Mineral repair mortar / Lithomex-type system	Mineral restoration mortar	Loss compensation and edge reconstruction	Product/formulation dependent	Designed for masonry exposure	Generally favorable relative to epoxy	Compatible texture and weathering; reduces use of	Not primary structural adhesive	Preferred for appropriate loss compensation

A.2 Comparative Matrix

Table A.1: Adhesive and Repair-Material Property Comparison Matrix

Material / System	Material Type	Principal Intended Role	Selected Reported Properties	Exterior / Moisture Considerations	Retreatability	Principal Conservation Strengths	Principal Conservation Limitations	Preliminary TP3 Classification
						polymer as fill		
Monument setting compound	Oil-/putty-based or proprietary setting material	Exterior perimeter joint; secondary setting	Product dependent	Intended for monument joints and exterior setting	Generally favorable relative to structural resin	Maintainable; workable; accommodates limited movement; established monument use	Potential staining or hardening depending on formulation; composition may be less well characterized	Preferred candidate for appropriate perimeter joints
Lead wedge	Soft metallic bearing material	Alignment, joint spacing, local bearing	Highly malleable; creep under sustained compression	Durable in protected joint; occupational lead precautions required	High mechanically	Conformable; adjustable; replaceable; long monument-setting history	Creep; point-loading risk if undersized; health considerations	Preferred bearing-adjustment material where appropriate
Stainless-steel pin/dowel	Mechanical reinforcement	Positive structural anchorage	High strength; elastic modulus much higher than marble	Excellent corrosion resistance in proper grade	Low	Predictable positive restraint; appropriate where structural need is high	Drilling removes original stone; concentrated load transfer; difficult retreatment	Preferred where mechanical restraint is demonstrated necessary

A.3 Interpretation

The matrix demonstrates that no single material optimizes every conservation property. Materials with the greatest chemical retreatability do not necessarily produce the least damaging mechanical failure, and materials with the closest mineral chemistry do not necessarily provide the tensile behavior required for structural fracture repair. Selection should therefore be made through the treatment framework described in Chapter 19 rather than by assigning a universal ranking to individual products.

Appendix B: Adhesive and Structural Treatment Selection Decision Tree

B.1 Purpose

This decision tree converts the treatment philosophy developed in Chapters 18–20 into a field-oriented sequence. It is designed to identify the **required level of intervention before selecting a product**.

It should not substitute for engineering or specialist evaluation when monument size, geometry, condition, or public-safety consequence exceeds the reasonable competence of routine preservation work.

B.2 Decision Sequence

STEP 1 — Is the monument currently safe to examine and handle?

NO:

Stabilize temporarily. Restrict access if necessary. Obtain qualified rigging, monument-setting, conservation, or engineering assistance before proceeding.

YES:

Proceed to Step 2.

STEP 2 — Is the stone at the proposed load-transfer zone sufficiently sound?

Consider granular disintegration, deep sugaring, delamination, major cracking, previous drill damage, edge loss, and substrate cohesion.

NO:

Do not simply select a stronger adhesive. Reconsider support, consolidation where separately justified, alternative load paths, reduced reassembly, external support, or non-reassembly.

YES:

Proceed to Step 3.

STEP 3 — Has the cause of the original failure been identified and corrected or judged inactive?

Potential causes include foundation settlement, frost, drainage, corrosion, impact, vegetation, poor bearing, previous repair, or structural geometry.

NO:

Address or accommodate the active cause before rigid reassembly.

YES:

Proceed to Step 4.

STEP 4 — What type of structural problem exists?

A. Close-fitting fracture through a tablet or structural stone section

Proceed to Step 5A.

B. Broad horizontal multi-piece monument interface

Proceed to Step 5B.

C. Internal void, delamination, or crack not requiring complete disassembly

Proceed to Step 5C.

D. Exposed perimeter joint only

Proceed to Step 5D.

E. Elevated, projecting, tall, narrow, or safety-critical element requiring positive restraint

Proceed to Step 5E.

STEP 5A — Close-Fitting Structural Fracture

Can the fracture be accurately aligned with limited missing material?

YES:

Evaluate a thin structural adhesive system.

Primary candidate: **AKEPOX 5010**, subject to sound marble and appropriate field conditions.

High-priority research alternative: **B-72 intervention layer + AKEPOX 5010**.

Specialized alternatives: HXTAL, Epo-Tek, Akepox 2000, thermoplastic acrylic systems where justified.

Does the repaired section experience high bending, unusual geometry, repeated previous failure, or safety-critical loading?

YES:

Evaluate whether mechanical reinforcement is structurally necessary.

NO:

Adhesive-only repair may represent the least invasive adequate intervention.

STEP 5B — Broad Horizontal Multi-Piece Interface

Can the component remain stable and properly aligned through bearing before adhesive is added?

NO:

Correct foundation, bearing, surface geometry, bedding, or support first. Do not use adhesive simply to make an unstable bearing condition appear stable.

YES:

Determine restraint demand.

Low restraint demand:

Level 1 — bearing and joint treatment only may be sufficient.

Moderate restraint demand:

Level 2 — stable bearing + lead + localized adhesive restraint + maintainable perimeter joint.

Primary current GG candidate for localized restraint: **Pratley Standard Setting Putty**.

High overturning, uplift, or safety demand:

Proceed toward Level 4 mechanical reinforcement or engineered structural bonding.

STEP 5C — Internal Void or Delamination

Is the void geometry injectable, and can injection occur without excessive pressure?

YES:

Consider mineral grout such as **IG10**, NHL grout, lime-pozzolan grout, or other compatible system according to stone condition and required mechanical role.

NO:

Alternative access or partial dismantling may be necessary.

If substantial tensile structural continuity is required, mineral grout may not be sufficient; evaluate structural adhesive or mechanical solution.

STEP 5D — Perimeter Joint

Is structural restraint already provided independently?

YES:

Use maintainable perimeter material appropriate to monument history and stone condition: monument setting compound, compatible lime mortar, lead pointing, or other justified material.

NO:

Do not assume perimeter pointing alone will solve the structural problem. Return to structural assessment.

STEP 5E — Positive Mechanical Restraint

Can sufficient sound stone safely accept drilling with adequate edge distance and embedment?

NO:

Mechanical reinforcement may be unsafe. Evaluate alternative support or non-reassembly.

YES:

Design pin/dowel/anchor system appropriate to load, geometry, stone thickness, and failure consequence.

Use corrosion-resistant reinforcement such as appropriate stainless steel or validated composite material where justified.

Document hole position, size, depth, pin material, anchoring resin/grout, and intended structural role.

B.3 Final Selection Questions

Before treatment begins, the practitioner should be able to answer all of the following:

1. What load is the intervention intended to carry?
2. Why is the proposed material necessary?
3. What historic material will be permanently altered?
4. What would happen if the repair were omitted?
5. What is expected to fail first under overload?
6. What happens if that component fails?
7. Can a less invasive adequate system accomplish the same purpose?
8. How would the repair be retreated in the future?
9. Has the location of permanent material been documented?
10. What condition will trigger future reassessment?

If these questions cannot be answered, material selection is premature.

Appendix C: Supplemental Monument Configuration and Load Diagrams

C.1 Purpose

The principal structural diagrams developed for this paper are incorporated directly into the chapters where their concepts are introduced. Figures illustrating dead-load transfer, tablet bending, bearing quality, intervention layers, limited-bond reassembly, pin and dowel load transfer, failure modes, treatment selection, and environmental aging therefore appear within the main body rather than being repeated in this appendix.

Appendix C provides a smaller set of **supplemental configuration and load diagrams** intended to support field interpretation of monument geometry. These figures expand upon the principal diagrams without establishing additional treatment rules. They are particularly useful for distinguishing how different monument forms obtain stability and how the same external force can produce different structural demands depending upon geometry, support, and connection.

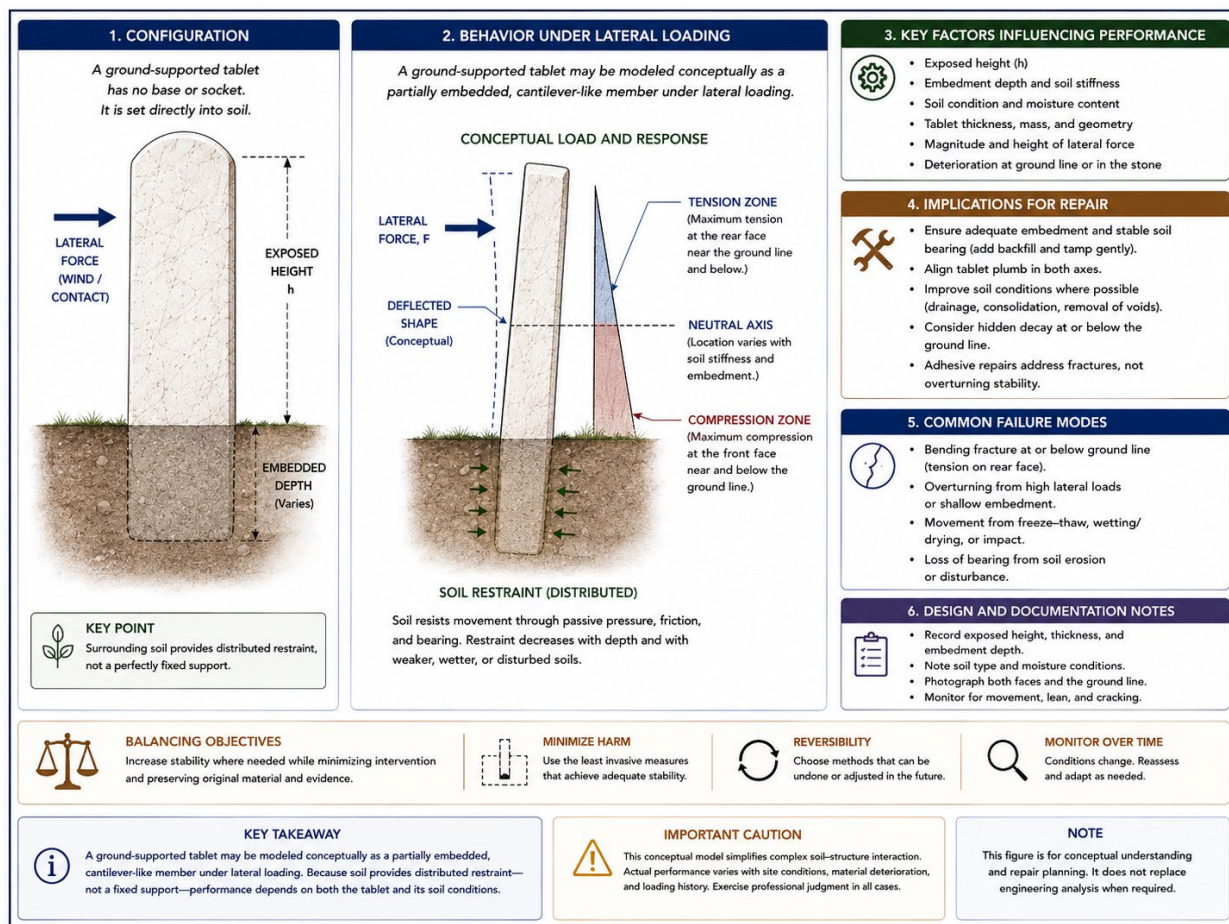
The diagrams are conceptual rather than engineered analyses. Arrows indicate general load direction and probable force transfer; their size should not be interpreted as a calculated magnitude. Likewise, illustrated stress concentrations, bearing zones, and potential fracture locations represent mechanically plausible behavior rather than finite-element analysis of a particular monument.

Treatment decisions should always be based upon the actual stone condition, geometry, foundation, environmental exposure, previous repairs, and consequences of component movement.

Figure C.1

Ground-Supported Tablet: Embedment, Bending, and Grade-Line Stress

The structural behavior of a ground-supported tablet is shown in Figure C.1. Its stability depends primarily upon below-grade embedment and distributed soil restraint, while lateral loading of the exposed portion can produce bending and elevated stress near the transition at grade.



Structural Interpretation

A ground-supported tablet derives most of its stability from embedment and surrounding soil rather than from an adhesive, setting compound, or pin connection at its base. When such a tablet fractures above grade, structural adhesive is therefore being asked primarily to restore continuity through a bending member. This differs fundamentally from a multi-piece monument in which a broad upper component is already supported by gravity on a separate base.

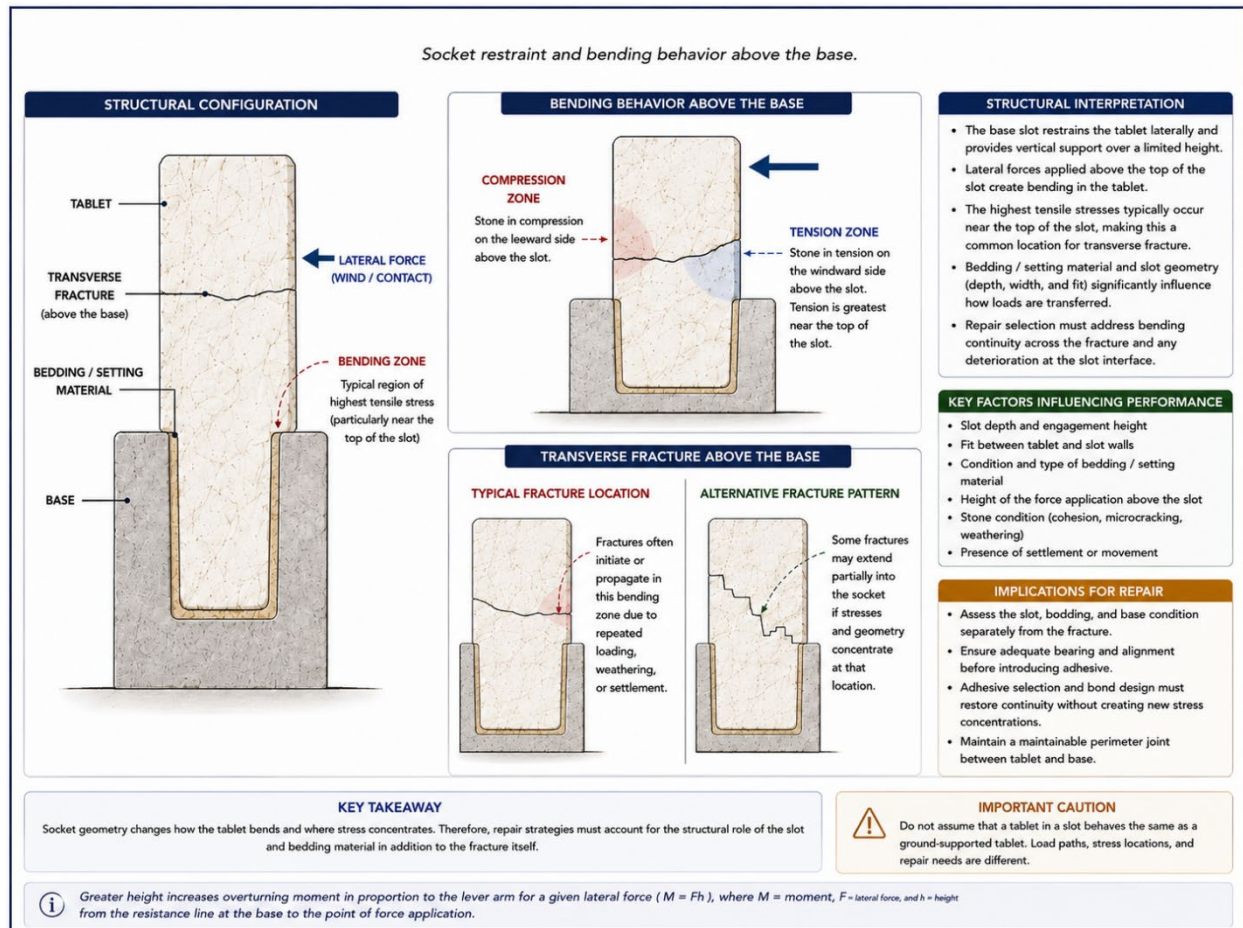
A repaired fracture should consequently be evaluated according to tablet thickness, fracture geometry, condition of the surrounding marble, expected bending demand, and whether the embedded portion remains stable. Increasing bond strength cannot compensate for continued movement at grade or inadequate support below ground.

Cross-reference: See Figure 4.2, *Tablet Bending Versus Monument Bearing*, and Chapters 4, 7, 16, and 18.

Figure C.2

Slotted-Base Tablet: Socket Restraint and Bending Above the Base

Figure C.2 illustrates the intermediate structural condition created when a tablet is restrained within a slotted stone base. The socket provides lateral support over a limited height, making bedding condition, socket contact, and the transition immediately above the base relevant to both fracture formation and subsequent repair.



Structural Interpretation

A slotted-base tablet does not behave structurally like a ground-supported tablet or a broad die-and-base monument. The socket provides restraint over a relatively short section of the tablet and can create localized bending and contact stresses near the top of the base. Deteriorated bedding, hard cementitious infill, corrosion from concealed metal, or previous adhesive can substantially alter this original load path.

A transverse fracture above the base may therefore require restoration of bending continuity, but treatment of the fracture should not occur without examining the socket itself. If the base continues to restrain the tablet unevenly or concentrates load at one edge, strengthening the fracture alone can simply relocate the next failure.

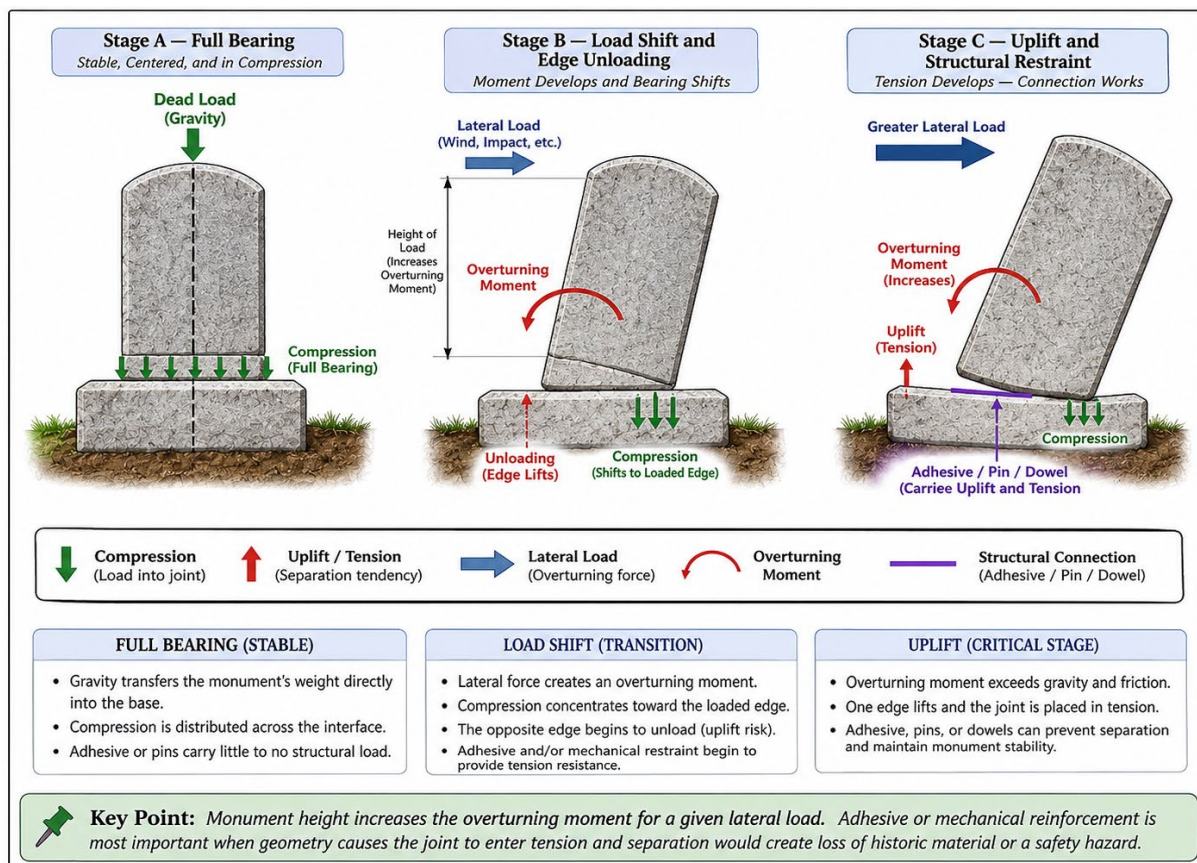
Where resetting the tablet within its socket is required, bedding or setting materials should perform their own function rather than becoming an extension of the structural adhesive joint.

Cross-reference: See Figures 4.2 and 6.1 and Chapters 4, 6, 7, and 18.

Figure C.3

Progressive Overturning of a Multi-Piece Monument

The changing load path produced by lateral force is shown progressively in Figure C.3. As compression shifts toward one edge and the opposite edge begins to unload, an interface that originally carried primarily compression can enter uplift, at which point adhesive or mechanical restraint assumes a substantially different structural role.



Structural Interpretation

The sequence demonstrates why adhesive or reinforcement in a broad monument joint may perform relatively little structural work during ordinary dead-load conditions yet become critical during rocking or overturning. It also explains why monument height matters. The same horizontal force applied higher above the joint produces a larger overturning moment.

This relationship is central to deciding whether bearing and limited restraint are sufficient or whether positive mechanical reinforcement is justified. A low, broad die and a tall narrow monument should not receive identical connection systems solely because both rest on horizontal bases.

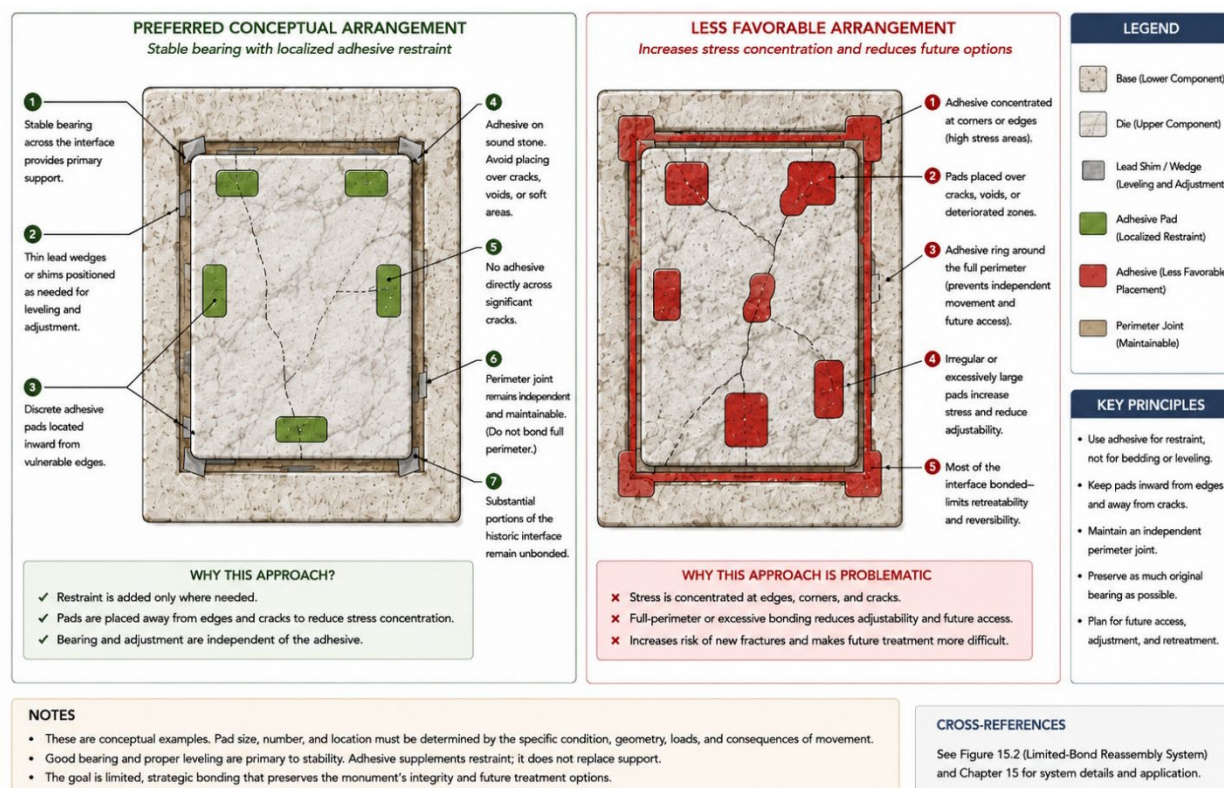
The practical question is not simply how strongly the two stones can be connected. It is **when the monument geometry causes that connection to enter tension and how consequential separation would be once it does.**

Cross-reference: See Figure 4.1, *How a Multi-Piece Monument Carries Dead Load*; Figure 15.2, *GG Limited-Bond Reassembly System*; Figure 16.1, *Pin/Dowel Load Transfer and Stress Concentration*; and Chapters 4, 15, 16, and 19.

Figure C.4

Localized Adhesive Restraint: Plan-View Placement Principles

Figure C.4 compares conceptually favorable and unfavorable approaches to localized adhesive placement. The comparison emphasizes that reducing adhesive quantity is not sufficient by itself; pad location, edge distance, substrate condition, bearing, and preservation of an independently maintainable perimeter remain integral to the limited-bond strategy.



Note: This diagram is conceptual and not to scale. Pad shapes, sizes, and locations are illustrative only and should be adapted to the specific monument.

Structural Interpretation

Localized bonding is not conservation-favorable merely because less adhesive is used. A smaller bond positioned poorly can concentrate stress more aggressively than a larger bond positioned within sound stone. Pad area, pad location, edge distance, bearing, and the load being resisted must therefore be considered together.

The objective of limited-bond reassembly is to use permanent adhesive only where supplemental restraint is needed while preserving independent bearing and future access. The method should not be understood as applying small random quantities of putty beneath a monument.

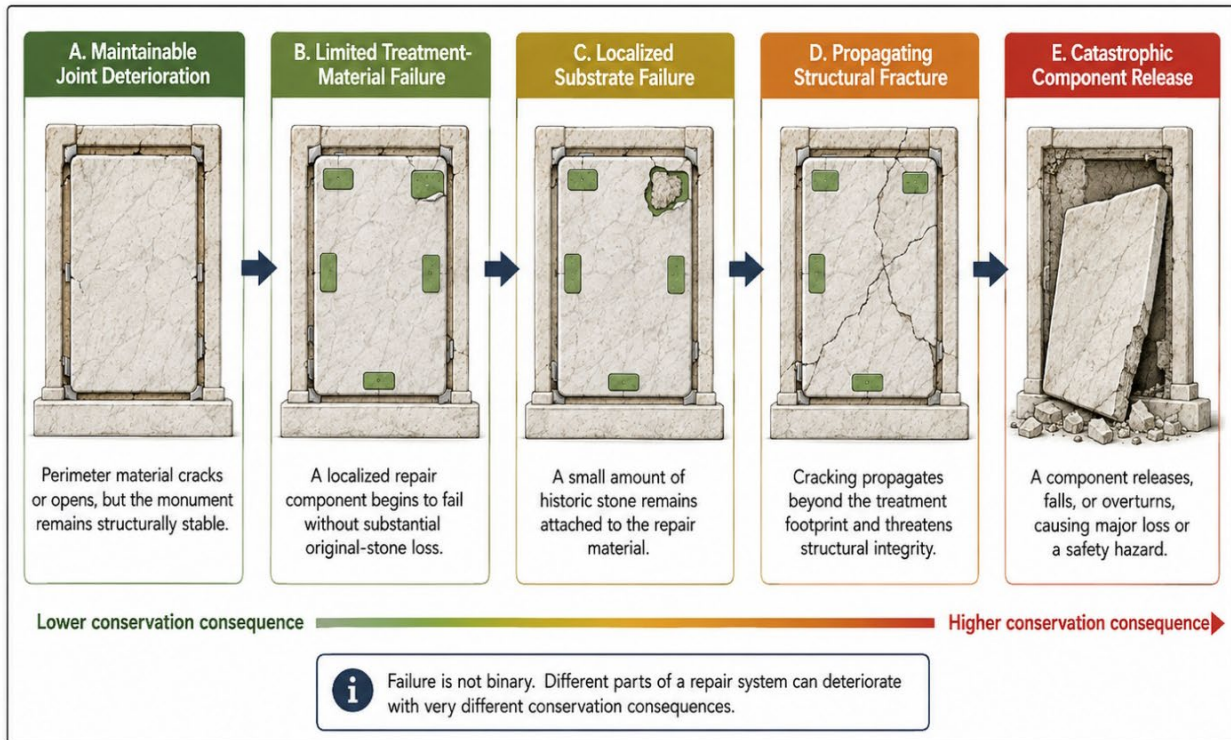
No universal number, dimension, or percentage of adhesive pads is established by this paper. Those variables remain part of the experimental research agenda described in Chapter 22.

Cross-reference: See Figure 15.2, Chapter 15, Chapter 20, and Appendix G.

Figure C.5

Failure Progression: From Maintainable Change to Catastrophic Loss

Figure C.5 presents a conceptual range of repair-system outcomes from maintainable joint deterioration to catastrophic component release. The sequence is not intended as an inevitable progression; rather, it demonstrates that different forms of deterioration can carry markedly different consequences for original material and public safety.



Note: This figure is conceptual and does not imply that every repair progresses sequentially through all five stages. Some repairs may remain stable with maintainable change, while others may fail suddenly depending on load, geometry, substrate condition, and the consequences of component movement.

Structural Interpretation

The figure should not imply that every repair progresses sequentially through all five conditions. A severe impact may move immediately from stability to catastrophic failure, while a perimeter material may require repeated maintenance for decades without progression to structural damage.

Its purpose is to demonstrate that **failure is not binary**. A repair is not simply “holding” or “failed.” Different parts of a treatment system can deteriorate at different times and with very different conservation consequences.

A repair in which accessible perimeter material requires renewal may be functioning precisely as intended. Conversely, an adhesive joint that remains visually perfect while a new crack develops through adjacent marble represents a more serious structural change even though the adhesive itself has not failed.

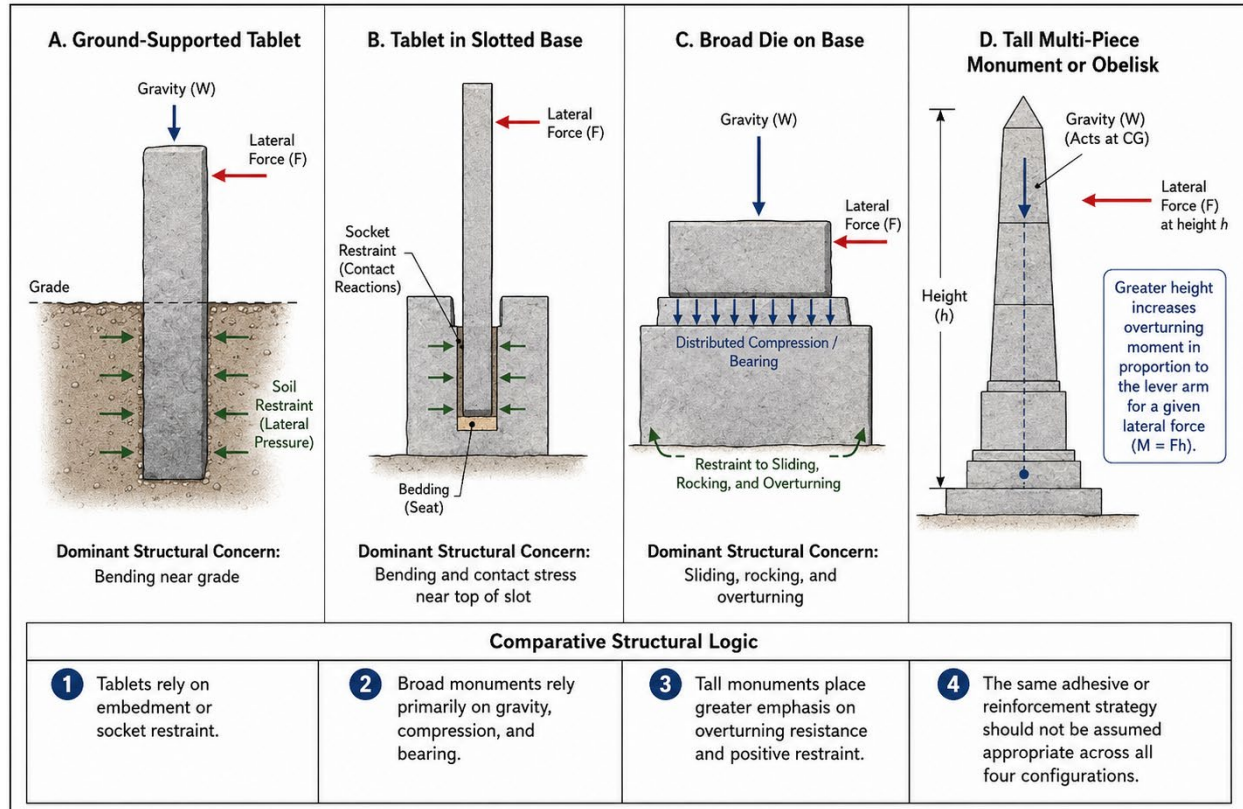
For this reason, monitoring should evaluate the entire monument and its support system rather than focusing only upon whether the adhesive seam remains intact.

Cross-reference: See Figure 17.1, *Common Failure Modes of Adhesive Repair*; Figure 23.1, *Structural Capacity Versus Conservation Consequence*; Chapters 17, 23, and 28; and Appendix H.

Figure C.6

Functional Load Paths Across Four Common Monument Configurations

The effect of monument configuration on structural demand is compared in Figure C.6. Ground-supported tablets, slotted tablets, broad die-and-base monuments, and tall multi-piece monuments derive stability through different combinations of embedment, socket restraint, bearing, gravity, friction, and positive connection; consequently, the same adhesive or reinforcement strategy should not be assumed appropriate across all four configurations.



Note. Arrows indicate general load direction and probable force transfer. For a fixed lateral force F , overturning moment increases in direct proportion to the height h of the force application ($M = Fh$).

Structural Interpretation

The comparison reinforces a central conclusion of this paper: **monument type determines what the repair is being asked to do**. A transverse adhesive joint in a thin tablet, a horizontal setting joint beneath a heavy die, and a pinned connection in a tall monument cannot be evaluated by the same simple measure of adhesive strength.

The treatment sequence should begin with the original structural logic of the monument. Adhesive, grout, setting material, lead, or mechanical reinforcement should then be introduced only to perform the specific functions that the existing geometry cannot provide reliably.

This principle applies to both marble and, with appropriate material-specific evaluation, multi-piece granite monuments. Granite differs substantially from marble in substrate cohesion, porosity, mineralogy, stiffness, and weathering behavior, but the structural distinction among bearing, sliding restraint, uplift resistance, and mechanical reinforcement remains relevant.

Cross-reference: See Figures 1.1, 4.1, 4.2, 15.1, 15.2, and 20.1.

Appendix D: Common Adhesive and Structural Repair Failure Modes

D.1 Failure Reference Matrix

Table D.1: Common Adhesive and Structural Repair Failure Modes

Failure Mode	Visual Indicators	Likely Contributing Factors	Conservation Significance	Recommended Response
Adhesive-interface failure	Adhesive separates cleanly from stone	Contamination, moisture incompatibility, poor wetting, inadequate cure, low adhesion	Can be favorable if above required service threshold and stone remains intact	Diagnose substrate and surface preparation before rebonding
Cohesive adhesive failure	Adhesive remains on both surfaces but fractures internally	Excessive load, voids, poor mixing, thick section, brittle cure	Potentially favorable if treatment fails before stone and adequate service strength was achieved	Assess whether capacity was adequate; remove/replace resin as appropriate
Superficial cohesive marble loss	Thin marble layer remains attached to adhesive	Weathered surface zone, strong bond, sugaring	Indicates substrate-limited joint	Reduce restraint or relocate bonding; reassess stone cohesion
Deep marble breakout	Thick fragment/cone of original stone removed	High bond capacity, stress concentration, pad near edge, pin anchorage	Poor failure hierarchy where load was not extraordinary	Reconsider bonded area, reinforcement, and surrounding stone condition
Crack migration	New fracture forms parallel or adjacent to old repair	Repair stronger/stiffer than neighboring stone; pre-existing microcracks	Can indicate restored original joint but new loss of untreated fabric	Record load context; consider whether restraint is excessive

Failure Mode	Visual Indicators	Likely Contributing Factors	Conservation Significance	Recommended Response
Edge breakout	Corner or edge fractures near pad/pin/wedge	Insufficient edge distance, deteriorated edge, concentrated load	Avoidable material loss in many cases	Change pad/pin location; increase surrounding sound stone
Full-area bond + remote fracture	Adhesive joint intact; crack develops elsewhere	Rigid structural coupling, continuing settlement, load redistribution	Indicates repair may be concealing rather than correcting movement	Reassess foundation and load path
Perimeter cracking	Setting compound or mortar cracks/opening	Normal aging, minor movement, shrinkage	May represent maintainable sacrificial behavior rather than structural failure	Inspect underlying stability; renew joint if appropriate
Lead extrusion/creep	Wedge protrudes or joint width changes	Excessive localized load, sustained compression, poor placement	Bearing system changing; adhesive may begin carrying unintended loads	Reassess support and reset if necessary
Pin-hole breakout	Crack runs from dowel hole to edge	Oversized pin, insufficient edge distance, weak marble, excessive stiffness	Significant irreversible failure	Redesign reinforcement or abandon pin approach
Pin-end cracking	Radial or axial crack beginning at end of dowel	Abrupt load transfer, excessive stiffness, short embedment	Concentrated internal failure	Reconsider pin geometry/material

Failure Mode	Visual Indicators	Likely Contributing Factors	Conservation Significance	Recommended Response
Corrosion-induced splitting	Rust staining, expanding crack near metal	Ferrous pin/cramp corrosion	Active destructive mechanism	Remove/replace corroding metal where feasible
Creep deformation	Gradual joint displacement without fracture	Thermoplastic adhesive, elastomer, lead, thick putty under sustained load	Serviceability failure may precede structural failure	Reduce sustained load on polymer; restore bearing
UV yellowing	Exposed resin becomes yellow/brown	Polymer formulation, sunlight	Aesthetic degradation; may prompt invasive retreatment	Limit exposed resin; select light-stable material
Resin staining halo	Darkened marble adjacent to joint	Low-viscosity resin penetration, migrating components	Permanent visual alteration	Improve application control; consider intervention layer
Moisture concentration	Persistent darkening, biological growth, salts beside bond	Altered drying pathway, broad impermeable layer	May accelerate adjacent stone deterioration	Reassess water management and treatment extent
Grout cracking	Fine fracture through mineral fill	Shrinkage, movement, insufficient cure, high stiffness	May be benign or signal loss of continuity	Determine whether stone or grout remains stable
Grout debonding	Void returns between grout and stone	Shrinkage, poor injectability, contamination	Treatment no longer distributing load	Reinject only after determining cause

Failure Mode	Visual Indicators	Likely Contributing Factors	Conservation Significance	Recommended Response
Catastrophic release	Component falls, overturns, or fully separates	Under-strength repair, severe external load, foundation failure	Highest safety and conservation consequence	Secure area; document failure before intervention if safe

D.2 Field Failure Documentation

When failure occurs, record:

- date discovered;
- whether failure was sudden or progressive;
- recent storm, impact, vandalism, freeze-thaw, maintenance, or construction events;
- photographs before movement;
- position and orientation of every fragment;
- adhesive residue on each surface;
- approximate percentage of adhesive versus marble failure;
- maximum stone-loss depth;
- new crack length;
- condition of bearing and foundation;
- condition of lead, perimeter material, and pins;
- whether the component remained safe or became hazardous.

Appendix E: Field Condition Assessment Form

E.1 Monument Identification

Cemetery: _____

Municipality / State: _____

Section / Lot / GPS or Other Location Reference: _____

Name(s) on Monument: _____

Approximate Date of Monument: _____

Assessment Date: _____

Assessors: _____

Permission / Property Contact: _____

E.2 Monument Type

- ☐ Ground-supported tablet
- ☐ Tablet in slotted base
- ☐ Die and base
- ☐ Multi-tier monument
- ☐ Obelisk
- ☐ Column / pedestal
- ☐ Urn / finial
- ☐ Sculptural monument
- ☐ Ledger
- ☐ Mausoleum / architectural stone
- ☐ Other: _____

Number of structural stone components: _____

Approximate total height: _____

Principal stone material: _____

- ☐ Marble
- ☐ Granite
- ☐ Limestone
- ☐ Sandstone

- ☐ Slate
 - ☐ Concrete / cast stone
 - ☐ Mixed materials
 - ☐ Uncertain
-

E.3 Current Safety Condition

- ☐ Stable for examination
- ☐ Requires temporary support before manipulation
- ☐ Elevated loose component
- ☐ Severe lean
- ☐ Active rocking
- ☐ Risk of collapse
- ☐ Public access restriction recommended
- ☐ Specialist rigging / engineering review recommended

Comments:

E.4 Foundation and Ground Conditions

Foundation visible? ☐ Yes ☐ No

Base level? ☐ Yes ☐ No ☐ Uncertain

Observed conditions:

- ☐ Settlement
- ☐ Differential settlement
- ☐ Erosion
- ☐ Exposed foundation
- ☐ Frost movement
- ☐ Tree roots
- ☐ Standing water
- ☐ Poor drainage
- ☐ Soil loss

- ☐ Previous foundation repair
- ☐ Stable / no significant issue observed

Comments:

E.5 Marble / Stone Condition

Surface condition at proposed treatment area:

- ☐ Sound crystalline surface
- ☐ Minor weathering
- ☐ Moderate grain loss
- ☐ Sugaring / granular disintegration
- ☐ Flaking / scaling
- ☐ Delamination
- ☐ Major crack network
- ☐ Previous spall
- ☐ Structural loss
- ☐ Hollow / questionable internal condition
- ☐ Salt deposits
- ☐ Biological growth
- ☐ Persistent dampness

Assessment of load-bearing suitability:

- ☐ Appears adequate
 - ☐ Marginal — treatment modification required
 - ☐ Inadequate for concentrated structural bonding/pinning
 - ☐ Specialist assessment required
-

E.6 Fracture Assessment

Fracture type:

- ☐ Clean recent fracture
- ☐ Old weathered fracture
- ☐ Irregular fracture
- ☐ Close fitting

- ☐ Missing material
- ☐ Previous bonded fracture
- ☐ Multiple fragments
- ☐ Fracture extends into other cracks
- ☐ Previous pin holes intersect repair zone

Dry fit achievable? ☐ Yes ☐ No ☐ Not yet tested

Approximate maximum gap after dry fit: _____

Significant edge loss? ☐ Yes ☐ No

Carving / inscription crosses fracture? ☐ Yes ☐ No

E.7 Previous Repairs

Observed materials:

- ☐ Epoxy
- ☐ Polyester resin
- ☐ Silicone / caulk
- ☐ Portland cement
- ☐ Lime mortar
- ☐ Injection grout
- ☐ Lead
- ☐ Iron pin / cramp
- ☐ Stainless pin
- ☐ Fiberglass / composite pin
- ☐ Repair mortar
- ☐ Consolidant
- ☐ Unknown polymer
- ☐ Other: _____

Previous repair stable? ☐ Yes ☐ No ☐ Partially

Removal required for new treatment? ☐ Yes ☐ No ☐ To be determined

E.8 Moisture and Environmental Exposure

- ☐ Full sun
- ☐ Partial sun

- ☐ Heavy shade
- ☐ Tree cover
- ☐ Irrigation exposure
- ☐ Road / deicing salt exposure
- ☐ Flooding history
- ☐ High biological growth
- ☐ Ground moisture
- ☐ Open joint allowing water entry
- ☐ Freeze-thaw climate
- ☐ Coastal / marine exposure

Active moisture problem requiring correction? ☐ Yes ☐ No

E.9 Structural Function of Proposed Repair

Primary load condition:

- ☐ Compression / bearing
- ☐ Shear / sliding
- ☐ Bending
- ☐ Tension
- ☐ Peel / edge opening
- ☐ Rocking
- ☐ Overturning
- ☐ Sustained elevated fragment load
- ☐ Internal void stabilization
- ☐ Primarily weather/joint closure

Consequence if repaired joint releases:

- ☐ Minor displacement
 - ☐ Component remains supported
 - ☐ Likely additional fracture
 - ☐ Component may fall
 - ☐ Public-safety hazard
 - ☐ Damage to adjacent monuments
 - ☐ Unknown / requires structural review
-

E.10 Recommended GG Intervention Level

- ☐ **Level 1 — Bearing and Joint Treatment Only**
- ☐ **Level 2 — Limited-Bond Reassembly**
- ☐ **Level 3 — Structural Adhesive Reassembly**
- ☐ **Level 4 — Mechanically Reinforced Repair**
- ☐ **Do Not Reassemble at Present**
- ☐ **Specialist Review Required**

Rationale:

E.11 Proposed Material System

Structural adhesive: _____

Intervention layer: _____

Bearing material: _____

Pin / reinforcement: _____

Bedding material: _____

Perimeter joint material: _____

Loss compensation material: _____

E.12 Stop Criteria Identified Before Work

- ☐ Hidden cracks revealed
- ☐ Bearing cannot be restored
- ☐ Required adhesive area becomes substantially larger than planned
- ☐ Stone proves too weak for proposed bonding
- ☐ Pin edge distance inadequate
- ☐ Foundation instability discovered
- ☐ Safety condition exceeds project capability

- ☐ Previous repair cannot be removed without disproportionate damage
- ☐ Other: _____

Appendix F: Structural Repair Documentation Form

F.1 Treatment Identification

Treatment Record Number: _____

Cemetery: _____

Monument / Individual: _____

Treatment Date(s): _____

Lead Practitioner: _____

Team Members: _____

F.2 Treatment Objective

Describe the condition requiring intervention and what the treatment is intended to accomplish:

F.3 Failure Diagnosis

Observed failure:

Probable cause:

Cause corrected / accommodated how:

F.4 Treatment Level

- ☐ GG Level 1
- ☐ GG Level 2
- ☐ GG Level 3
- ☐ GG Level 4

Reason this level was selected:

Less invasive alternative considered:

Why not selected:

F.5 Foundation / Bearing Work

Foundation treatment performed:

Dry-fit observations:

Bearing condition after preparation:

Lead wedge locations and approximate dimensions:

Other bearing material:

F.6 Adhesive / Grout Record

Product: _____

Manufacturer: _____

Product type: _____

Batch / lot if available: _____

Mixing ratio: _____

Approximate quantity used: _____

Color / pigment / filler added: _____

Stone surface condition at application:

☐ Dry

☐ Slightly damp

☐ Other: _____

Air temperature: _____

Approximate stone temperature if measured: _____

Weather: _____

F.7 Intervention Layer

☐ None

☐ Paraloid B-72

☐ Paraloid B-48N

☐ Other: _____

Concentration: _____

Solvent: _____

Application method: _____

Drying period: _____

Evidence layer was dry before secondary adhesive:

F.8 Localized Adhesive Map

Attach plan-view diagram and photographs.

Record:

- number of pads;
- approximate pad dimensions;
- distance from nearest edge;
- relationship to cracks;
- relationship to lead wedges;
- orientation relative to monument front.

Pad 1: _____

Pad 2: _____

Pad 3: _____

Pad 4: _____

Additional pads: _____

F.9 Pin / Dowel Record

☐ No mechanical reinforcement

If used:

Material: _____

Diameter: _____

Length: _____

Hole diameter: _____

Embedment depth: _____

Number of pins: _____

Pin location / orientation: _____

Anchoring adhesive / grout: _____

Existing historic holes reused? ☐ Yes ☐ No

F.10 Perimeter Joint

Material: _____

Joint width: _____

Application method: _____

Historical basis for material selection, if applicable:

F.11 Cure

Bonding completed: Date _____ Time _____

Temporary restraint removed: _____

Manufacturer full-cure period: _____

Unexpected cure conditions:

F.12 Deviations From Treatment Plan

Describe any change from the pre-treatment plan and why it became necessary:

F.13 Final Condition

- ☐ Level
- ☐ Plumb
- ☐ Stable
- ☐ No rocking
- ☐ Fracture aligned
- ☐ Perimeter joint complete
- ☐ Adhesive squeeze-out controlled

- ☐ Visible repair acceptable
- ☐ Existing cracks unchanged

Final observations:

F.14 Monitoring Recommendation

- ☐ Post-cure baseline completed
- ☐ Inspect after first winter / full seasonal cycle
- ☐ Inspect at approximately 1 year
- ☐ Incorporate into annual cemetery condition assessment
- ☐ High-priority experimental monitoring

Specific conditions to watch:

Appendix G: Proposed Experimental Test Protocol

G.1 Research Objective

To compare structural adhesive and monument-reassembly systems according to:

1. service capacity;
2. stiffness and displacement;
3. failure location;
4. original marble loss;
5. fracture propagation;
6. environmental durability; and
7. practical retreatability.

The research is not intended to identify the strongest adhesive. It is intended to determine which repair systems provide sufficient structural performance while producing the least damaging conservation outcome.

G.2 Research Phases

Phase 1 — Marble Characterization

Establish three substrate populations:

- sound reference marble;
- artificially weathered marble;
- naturally weathered sacrificial marble where ethically available.

Record:

- parent slab or source;
- grain orientation where known;
- mass;
- dimensions;
- visible condition;
- ultrasonic P-wave velocity;
- water uptake or porosity where laboratory resources permit.

Phase 2 — Material-Scale Joint Testing

Test selected adhesive systems under common specimen geometry.

Primary groups:

- A. AKEPOX 5010
- B. Pratley Standard Setting Putty
- C. Tenax Domo 10
- D. Paraloid B-72 structural formulation
- E. B-72 + AKEPOX 5010
- F. B-72 + Pratley
- G. IG10 in appropriate-width mineral joint
- H. Conventional polyester comparator

Optional secondary groups:

- I. HXTAL NYL-1
- J. B-72/B-48N blend
- K. Epo-Tek 301-2
- L. Akepox 2000

Phase 3 — Tablet-Fracture Simulation

Prepare thin marble beams or plates containing controlled transverse fractures.

Compare repaired specimen behavior under flexural loading with:

- intact unfractured marble controls;
- fractured unrepaired controls where safe/meaningful;
- direct 5010;
- direct B-72;
- B-72 + 5010;
- Domo 10;
- polyester comparator;
- other selected systems.

Phase 4 — Multi-Piece Monument Mock-Ups

Compare:

System A: full-area structural epoxy

System B: localized adhesive without optimized bearing

System C: stable bearing + lead + localized Pratley + maintainable perimeter

System C2: stable bearing + lead + B-72 + Pratley + maintainable perimeter

System D: mechanical dowel reinforcement

System E: mineral/bearing system without structural adhesive

Phase 5 — Environmental Aging

Subject matched specimens to defined thermal, wet-dry, freeze-thaw, UV, and sustained-load conditions.

Phase 6 — Retreatability

Attempt controlled disassembly after aging and document intervention required and resulting stone loss.

G.3 Replication

Initial screening:

Target: minimum approximately six valid replicates per treatment/substrate condition.

Confirmatory testing:

Target: approximately ten to twelve or more valid replicates where pilot variance supports this number.

Final sample size should be refined using statistical power analysis based on observed pilot variability.

G.4 Randomization

After baseline characterization, assign specimens randomly to adhesive groups so that differences in initial marble condition are distributed as evenly as practical.

G.5 Fracture Preparation

Preferred tablet-fracture method:

1. Cut specimens to uniform dimensions.
2. Introduce a shallow notch only sufficient to control approximate fracture location.
3. Fracture mechanically rather than saw fully through.
4. Retain original fragment pairing.
5. Record fracture surface photographically.
6. Rejoin without intentional grinding of the fracture.

This preserves irregular fracture topography while improving repeatability of fracture location.

G.6 Surface Preparation

Use conservation-oriented cleaning rather than industrial surface roughening.

Record:

- water cleaning;
- solvent cleaning if used;
- brushing;
- removal of loose grains;
- presence or absence of prior material.

Do not abrade natural fracture surfaces merely to maximize adhesive performance unless abrasion itself is being tested as an independent variable.

G.7 Bond-Line Measurement

Measure bond width microscopically or photographically where practical.

For putty specimens, record:

- pad footprint;
- pad thickness;
- pad volume.

For intervention layers, record:

- acrylic concentration;
- solvent;
- application mass where feasible;
- number of coats;
- drying period.

G.8 Cure

Follow manufacturer ratios and minimum temperature requirements.

Do not mechanically test at handling strength where full cure requires longer.

Suggested minimum full-cure condition:

- AKEPOX 5010: seven days at controlled room conditions unless alternative manufacturer-supported cure is used.
- Pratley: minimum 24 hours, with longer standardized cure preferred for cross-material comparison.

- B-72: drying confirmed beyond apparent surface dryness; mass-stability criterion preferred where feasible.
- Mineral grout: sufficient hydraulic curing period to reach stable comparison condition, potentially 28 days depending on product and research design.

G.9 Mechanical Test Outputs

Every mechanical test should record:

- preload;
- load-versus-displacement curve;
- first measurable movement;
- first visible crack;
- peak load;
- displacement at peak;
- load at complete separation;
- residual load after initial damage;
- failure location.

G.10 Failure Surface Documentation

After failure:

1. Photograph both surfaces orthogonally with scale.
2. Identify adhesive residue.
3. Estimate percentage:
 - adhesive-interface failure;
 - cohesive adhesive failure;
 - cohesive marble failure.
4. Measure maximum marble-loss depth.
5. Estimate damaged area.
6. Record new crack length.
7. Retain representative fragments.

Where available, 3-D scanning or photogrammetry should estimate stone-loss volume.

G.11 Multi-Piece Shear Test

Apply realistic vertical dead load.

Increase horizontal force slowly.

Record:

- force at first slip;
- displacement;
- pad or perimeter engagement;
- force at major movement;
- failure mechanism;
- stone loss.

G.12 Multi-Piece Overturning Test

Apply lateral load at known height above interface.

Calculate applied moment from force × vertical lever arm.

Record:

- edge unloading;
- initial uplift;
- adhesive engagement;
- crack initiation;
- pad release;
- maximum moment;
- final failure.

G.13 Bonded Area Series

Suggested preliminary area conditions:

- low-area localized restraint;
- medium-area localized restraint;
- high-area localized restraint;
- full-area control.

Exact percentages should be selected only after realistic monument-interface modeling.

Do not describe any tested percentage as universally safe.

G.14 Statistical Analysis

Report:

- mean;
- median;
- standard deviation;
- coefficient of variation;
- confidence intervals where useful;
- distribution of failure modes.

Use appropriate statistical comparison after determining data distribution and sample size.

Failure-mode and stone-loss results should remain visible alongside conventional strength statistics.

G.15 Research Ethics

No intact historic grave marker or culturally significant monument should be destroyed for testing.

Naturally weathered historic stone should be used only where it is legally available, culturally deaccessioned, non-significant, or otherwise approved for destructive research.

Appendix H: Failure Classification and Conservation Scoring System

H.1 Purpose

This appendix provides a provisional framework for evaluating the conservation consequence of structural repair failure. It is intended for research comparison and structured field observation.

The system is **not** an established industry standard and requires validation through experimental use.

H.2 Primary Failure Class

Class A — Treatment Material Failure

Failure remains substantially within modern repair material.

Examples:

- cohesive adhesive fracture;
- setting-compound failure;
- mortar cracking;
- removable joint-material loss.

Class B — Adhesive Interface Failure

Separation occurs principally at the stone-treatment interface with negligible stone loss.

Class C — Superficial Substrate Failure

Adhesive removes loose grains or shallow surface material but does not produce deep breakout or structural crack propagation.

Class D — Localized Cohesive Stone Failure

Measurable original marble loss occurs beneath or adjacent to treatment but remains localized.

Class E — Propagating Structural Stone Failure

New crack extends significantly beyond repair footprint, deep spall develops, edge breaks out, or pin-related fracture develops.

Class F — Catastrophic / Hazardous Failure

Component falls, overturns, shatters, or presents immediate safety hazard.

H.3 Severity Level

Table H.1: Failure Severity Classification Levels

Level	Description
0	No measurable damage
1	Repair-material deterioration only
2	Negligible original stone loss
3	Localized measurable original stone loss
4	Significant fracture or loss affecting structural or carved material
5	Catastrophic fragmentation, collapse, or hazardous release

H.4 Conservation Failure Index — Provisional

A 0–100 Conservation Failure Index may be calculated using normalized component scores.

Proposed weighting:

Original marble volume lost — 30 points

Crack propagation beyond treatment — 20 points

Depth/severity of cohesive stone failure — 15 points

Loss of retreatability / joint accessibility — 15 points

Residual instability or hazardous release — 15 points

Visual or staining consequence — 5 points

Formula

$$CFI = V + C + D + R + H + A$$

where:

- **V** = normalized stone-volume loss score, maximum 30
- **C** = crack-propagation score, maximum 20
- **D** = substrate-depth score, maximum 15
- **R** = retreatability score, maximum 15
- **H** = hazard/residual-instability score, maximum 15
- **A** = aesthetic consequence score, maximum 5

Lower scores represent lower conservation consequence.

H.5 Example Component Scales

Stone Volume Loss — 0–30

- 0 = none
- 5 = loose grains only
- 10 = shallow localized spall
- 20 = substantial localized loss
- 25 = deep loss exceeding original bond footprint
- 30 = major fragmentation

Crack Propagation — 0–20

- 0 = none
- 5 = crack confined to bond edge
- 10 = crack extends modestly beyond treatment
- 15 = crack extends through significant portion of specimen
- 20 = major new structural fracture

Retreatability — 0–15

- 0 = clean future access / readily separated
- 5 = moderate intervention needed
- 10 = substantial mechanical or solvent intervention
- 15 = retreatment requires major original-material removal

Hazard / Residual Instability — 0–15

- 0 = component remains secure
- 5 = limited displacement but supported
- 10 = major movement requiring immediate intervention
- 15 = release, fall, collapse, or severe hazard

H.6 Structural Capacity Must Be Reported Separately

The CFI must **never** be used alone.

A weak adhesive releasing safely at an unacceptably low service load might receive an excellent CFI while constituting a poor repair.

Every CFI result must therefore be presented alongside:

- required or representative service threshold;
- measured first movement;
- ultimate load;
- reserve capacity.

H.7 Recommended Two-Axis Presentation

Plot:

X-axis: structural capacity or reserve capacity above service threshold

Y-axis: Conservation Failure Index

Preferred systems occupy the region of:

- adequate/high capacity; and
- low CFI.

Systems with low capacity and low damage are under-strength.

Systems with high capacity and high damage may be over-restrained.

This figure is recommended for the final experimental report.

Appendix I: Environmental Aging Protocol

I.1 Purpose

This protocol is intended to compare repair systems under controlled environmental stress relevant to exterior cemetery monuments. It is not intended to claim direct equivalence between laboratory cycles and a specified number of natural years.

I.2 General Experimental Structure

For each selected repair system, retain:

- unaged control group;
- thermal-cycled group;
- wet-dry group;
- freeze-thaw group;
- UV-exposed group where adhesive is visible;
- salt-exposed group where relevant;
- sustained-load group;
- combined-aging group.

Use matched marble populations.

I.3 Baseline Measurements

Before aging:

- photograph;
- weigh;
- measure dimensions;
- record joint width;
- measure ultrasonic P-wave velocity where possible;
- perform colorimetry on exposed light-colored joints where possible;
- record baseline stiffness through nondestructive proof loading where appropriate.

I.4 Thermal-Cycling Protocol — Preliminary

Final temperatures should be selected with laboratory partners and supported by realistic exterior stone-temperature data.

A reasonable **service-environment** screening concept may involve cycling between representative winter and summer surface temperatures without entering extreme thermal-damage ranges used in geological research.

Cycle stages should include:

1. controlled cooling;
2. low-temperature dwell;
3. controlled heating;
4. high-temperature dwell;
5. return to baseline.

Record heating/cooling rate and actual specimen temperature.

Avoid interpreting high-temperature accelerated marble-weathering protocols as direct cemetery simulation.

I.5 Wet-Dry Cycling

Suggested structure:

1. condition specimens to stable dry mass;
2. wet through a defined method:
 - partial immersion,
 - capillary uptake,
 - controlled spray/rain simulation,
 - or another documented technique;
3. maintain wet condition for defined period;
4. dry at controlled temperature and humidity;
5. repeat.

Record:

- wet mass;
- dry mass;
- drying time;
- visible moisture pattern;

- joint darkening;
- efflorescence;
- staining.

I.6 Freeze-Thaw Protocol

Define explicitly:

- pre-freeze saturation condition;
- minimum temperature;
- dwell at freezing temperature;
- thaw temperature;
- thaw duration;
- total cycles.

Use natural-stone standards as methodological references while acknowledging that cemetery adhesive assemblies require adaptation.

Possible comparison:

Moderate moisture condition: simulates typical wet winter stone.

High saturation condition: severe screening representing prolonged moisture or flooding.

Inspect at regular cycle intervals.

I.7 UV / Photo-Oxidative Exposure

Use only where adhesive or treatment material would realistically receive sunlight.

Record:

- exposure spectrum;
- irradiance;
- chamber temperature;
- moisture/rain component if used;
- duration.

Measure:

- adhesive color;
- adjacent marble color;
- cracking;
- chalking;

- loss of adhesion;
- surface hardness if appropriate.

I.8 Salt Exposure

Salt testing should be selective.

Recommended phases:

Moderate environmental screening

Low-concentration salt introduced through controlled capillary uptake.

Severe comparative screening

A more aggressive standardized natural-stone salt protocol.

Do not interpret severe sodium sulfate testing as a literal model of all cemetery salts.

Document:

- salt identity;
- concentration;
- temperature;
- drying conditions;
- crystallization location;
- mass loss;
- spalling.

I.9 Sustained Load

Multi-piece specimens should remain under realistic vertical compression during relevant environmental cycles.

Selected adhesive systems may also receive sustained:

- shear;
- eccentric compression;
- low-level uplift/tension.

Monitor displacement over time.

The purpose is to identify creep or progressive bearing changes not visible in short-duration destructive tests.

I.10 Cyclic Mechanical Movement

Apply repeated low-amplitude lateral loading at a level well below initial failure.

Record:

- stiffness change;
- accumulated displacement;
- joint opening;
- visible cracking;
- pad degradation.

Repeat before and after environmental aging where feasible.

I.11 Combined Aging Sequence

After individual vulnerabilities are understood, a combined cycle may include:

1. wetting;
2. freezing;
3. thawing;
4. drying;
5. elevated-temperature exposure;
6. return to baseline.

UV exposure may be incorporated for visible surfaces.

Combined testing should follow, not replace, individual mechanism testing.

I.12 Withdrawal Intervals

Rather than expose every specimen to one terminal number of cycles, remove matched groups at several intervals.

Example:

- early;
- intermediate;
- advanced.

Exact cycle counts should be determined after pilot testing.

This permits aging curves rather than a single before-and-after comparison.

I.13 Post-Aging Evaluation

Repeat baseline measurements.

Then perform destructive testing.

Report:

- retained capacity;
- change in stiffness;
- change in displacement;
- change in failure mode;
- change in CFI;
- change in retreatability.

I.14 Outdoor Correlation Program

Maintain matched specimens outdoors.

Recommended observations:

- quarterly during first year where practical;
- after major winter cycle;
- annual thereafter.

Record:

- visible cracking;
- joint width;
- yellowing;
- biological growth;
- salt deposits;
- moisture patterns;
- lead movement;
- alignment.

Selected specimens may be withdrawn for mechanical testing after defined natural exposure periods.

Appendix J: Manufacturer Technical Data Summary

J.1 Purpose

This appendix summarizes selected manufacturer information used in the paper. Product-specific statements in the main text are cited to the primary manufacturer or technical data sheet in APA author–date form; Appendix J serves as a consolidated internal reference and should not replace review of the current technical documentation before use.

Manufacturer data describe performance under the manufacturer's test conditions. They are not equivalent to independent testing on weathered historic marble.

J.2 Akepox 5010

Manufacturer/source: AKEMI GmbH (2022).

Material: Two-component epoxy resin adhesive with cycloaliphatic polyamine hardener.

Consistency: Gel-like / thixotropic enough for controlled stone bonding while permitting thin joints.

Mixing ratio: Approximately 2 parts component A to 1 part component B by weight or volume.

Working time around 20°C: Approximately 20–30 minutes.

Temperature sensitivity: Working time increases in cooler conditions and decreases substantially in warmer conditions. Manufacturer cautions against application below approximately 10°C.

Maximum stability: Approximately seven days under stated conditions.

Reported flexural strength: Approximately 60–70 N/mm².

Reported tensile strength: Approximately 30–40 N/mm².

Water absorption: Less than approximately 0.5%.

Principal stated characteristics: Very low shrinkage, little tension within adhesive layer, weather resistance, adhesion to slightly humid stone, comparatively low yellowing.

Substrate caveat: AKEMI states that bonding stability depends on the natural stone and that silicate-bound stone reacts better than carbonate-bound stone.

Removal: Hardened product cannot normally be removed with solvents.

TP3 relevance: Primary candidate for thin, close-fitting structural marble fractures.

J.3 Tenax Domo 10

Manufacturer/source: Tenax S.p.A (2023); Tenax USA (n.d.-b) for the current U.S. product description.

Material: Two-component thixotropic epoxy.

Mix ratio: 1:1 by weight according to current technical documentation.

Intended application: Strong bonding of marble, granite, stone, ceramic, engineered materials, including demanding fabrication applications.

Exterior use: Manufacturer identifies exterior capability and damp/wet-surface application.

Current TDS notes: Numerical adhesion data for white marble are not supplied in a form directly comparable with bulk tensile values used by other manufacturers.

Shore D: Approximately 62 after stated cure conditions.

Yellowing: Current technical documentation reports high yellowing under the listed Q-Sun simulated outdoor exposure.

TP3 relevance: Important fabrication-strength comparator; no clear routine conservation advantage over 5010 identified for white historic marble.

J.4 Tenax Elix

Manufacturer/source: Tenax USA (n.d.-c).

Material: Clear two-component knife-grade epoxy.

Principal characteristics: Clear appearance, low shrinkage, low-yellowing formulation, colorability, stone adhesion.

Exterior use: Manufacturer identifies interior/exterior applications.

TP3 relevance: Possible specialized alternative where visible optical characteristics are important.

J.5 HXTAL NYL-1

Manufacturer/source: HXTAL Adhesive, LLC (n.d.). Material: Two-component low-viscosity clear epoxy developed for conservation/restoration applications.

Mix ratio: Approximately 3:1 by weight.

Cure: Very slow relative to monument-fabrication epoxies; major cure development occurs over multiple days.

Reported tensile strength: Approximately 5,400 psi / 37 MPa.

Tensile modulus: Approximately 316,000 psi / 2.18 GPa.

Elongation: Approximately 3%.

Flexural strength: Approximately 10,100 psi / 70 MPa.

Flexural modulus: Approximately 365,000 psi / 2.5 GPa.

Principal characteristics: Water-white clarity, excellent resistance to yellowing.

TP3 relevance: Conservation benchmark demonstrating that conservation pedigree does not imply low structural strength.

J.6 Epo-Tek 301-2

Manufacturer/source: Epoxy Technology, Inc (n.d.).

Material: Clear low-viscosity two-part epoxy.

Principal characteristics: Long pot life, excellent wetting, high adhesion, optical applications.

Cure: Manufacturer provides elevated-temperature and extended room-temperature schedules.

Mechanical reporting: Includes lap shear and storage-modulus data under manufacturer's conditions.

TP3 relevance: Included in marble conservation research; useful specialized benchmark rather than routine cemetery adhesive.

J.7 Akepox 2000

Manufacturer/source: AKEMI GmbH (n.d.-a).

Material: Low-viscosity two-part epoxy.

Principal characteristics: Low curing shrinkage, weather resistance, good adhesion to slightly humid stone.

TP3 relevance: Included in marble conservation research; lower viscosity than 5010 makes resin penetration and field control especially relevant.

J.8 Pratley Standard Setting Putty

Manufacturer/source: Pratley (2023).

Material: Two-part hand-mouldable epoxy adhesive putty.

Mix: Equal portions of components kneaded to uniform color.

Gel time: Approximately 50 minutes at room temperature.

Hard set: Approximately four hours.

Full strength: Approximately 24 hours, dependent upon conditions.

Principal characteristics: Excellent adhesion to rigid materials, hard abrasion-resistant cure, ability to set underwater, mouldable form.

Mechanical-data limitation: Reviewed public literature does not provide the full tensile modulus, fracture toughness, and marble-specific structural data needed for direct conservation comparison.

TP3 relevance: Primary GG localized-restraint candidate; justification rests on limited-area geometry and stable independent bearing, not on assumed weakness.

J.9 Paraloid B-72

Manufacturer/source: Dow (n.d.-b); conservation-specific behavior is additionally evaluated by Podany et al (2001) and Vinçotte et al (2019).

Material: Thermoplastic acrylic copolymer.

Application: Supplied as solid resin and dissolved by conservator in selected solvent/concentration.

Principal characteristics: Clear, flexible film; excellent conservation history; resistant to yellowing and embrittlement under many conservation conditions.

Glass-transition temperature: Dry polymer generally reported around 39–40°C, with residual solvent capable of depressing the effective transition substantially.

Retreatability: Solvent-responsive after drying.

TP3 relevance: Structural thermoplastic adhesive and intervention-layer candidate; published marble testing demonstrates substantial bond capacity.

J.10 Paraloid B-48N

Manufacturer/source: Dow (n.d.-a); marble-adhesive testing is reported by Jorjani et al (2008).

Material: Thermoplastic acrylic.

Principal characteristics: Toughness, adhesion, flexibility, exterior coating applications.

TP3 relevance: Tested in marble conservation research independently and in combination with B-72; promising experimental structural acrylic.

J.11 Heritage IG10 Injection Grout

Manufacturer/source: U.S. Heritage Group (n.d.).

Material: Cementitious mineral injection grout without synthetic polymer binder.

Intended use: Stabilization and repair of historic masonry and concrete; crack and void injection.

Recommended crack scale: Manufacturer guidance includes approximately 1/16 to 1/4 inch ranges.

Reported 28-day compressive strength: Approximately 7,300 psi.

Reported bond strength: Approximately 1,815 psi.

Reported flexural strength: Approximately 1,700 psi.

Reported elastic modulus: Approximately 2,350 ksi / roughly 16 GPa.

Porosity: Approximately 6%.

Absorption: Approximately 4–6%.

TP3 relevance: Demonstrates why mineral grout should not automatically be described as weak or sacrificial; best aligned with appropriate voids and distributed cracks.

J.12 Polyester Stone Mastics

Representative product sources include AKEMI GmbH (n.d.-b) and Tenax USA (n.d.-a, n.d.-f, n.d.-g).

General characteristics: Rapid cure, easy tinting, polishability, good fabrication adhesion.

Common limitations: Polymerization shrinkage, brittle cure, permanence, and in many conventional products interior-only or limited UV recommendations.

TP3 relevance: Mechanically capable but generally not preferred for routine exposed historic marble where better exterior alternatives exist.

J.13 Monument Setting Compound

Formulations vary considerably by manufacturer; contemporary monument-setting examples are documented by Atlas Preservation (n.d.-b) and the Town of Nantucket (2022).

General intended function: Setting and perimeter closure of monument joints.

Common characteristics: Putty-like consistency, nonhardening or semi-hardening behavior, weather-resistant joint sealing.

TP3 relevance: Should generally be treated as perimeter/joint-management material rather than primary structural adhesive.

Appendix K: Terminology and Definitions

K.1. Definitions

Adhesion

The attraction and mechanical connection occurring at the interface between two different materials, such as adhesive and marble.

Adhesive Failure

Failure occurring primarily at the interface between adhesive and substrate rather than within either bulk material.

Adhesive Pad

A deliberately localized region of structural adhesive used to restrain a monument component rather than bond the entire available interface.

Anisotropy

Dependence of material properties upon direction. Calcite and many marbles display anisotropic thermal and mechanical behavior.

Bearing

Transfer of compressive force through physical contact between surfaces.

Bedding

Material or geometry used to distribute compressive load and support one monument component upon another. Bedding should be distinguished from structural bonding.

Bond

The structural connection produced between two materials through adhesive, mechanical interlock, chemical attraction, or combinations thereof.

Bond Area

The effective area over which adhesive transfers force between substrates.

Bond Line

The layer of cured adhesive existing between joined surfaces.

Bond-Line Thickness

The distance separating two joined substrates occupied by adhesive.

Capillary Absorption

Movement of liquid water through small pores under capillary forces.

Cohesive Adhesive Failure

Fracture occurring within the body of the cured adhesive rather than at the adhesive-substrate interface.

Cohesive Stone Failure

Failure occurring within the historic stone while the adhesive interface remains substantially intact.

Compression

A loading condition in which forces push material together.

Conservation Failure Index (CFI)

A provisional composite metric proposed in this paper for comparing original-material loss, crack propagation, retreatability, hazard, and aesthetic consequence following failure. It is not an established conservation standard.

Consolidant

A treatment intended to increase cohesion within weakened porous material through penetration and deposition or reaction of a binding phase.

Continuous Bonding

An adhesive strategy in which most or all of an available interface is permanently bonded.

Crack Migration

Formation or extension of a new fracture adjacent to or beyond an earlier repaired fracture.

Creep

Time-dependent deformation of a material under sustained load.

Dead Load

The permanent gravitational load produced by the weight of the monument or component itself.

Delamination

Separation of layers or zones within a material or composite system.

Dry Fit

Temporary assembly of monument components without permanent adhesive to evaluate fit, bearing, alignment, joint geometry, and treatment strategy.

Elastic Modulus / Young's Modulus

A measure of material stiffness describing the relationship between stress and elastic strain within a defined range.

Edge Breakout

Fracture extending from a loaded region, adhesive pad, drilled hole, pin, or wedge to a nearby free edge.

Efflorescence

Visible salt deposits formed when dissolved salts migrate to a surface and crystallize as water evaporates.

Embedment Depth

Length of a pin, dowel, or anchor extending into the receiving stone.

Epoxy

A thermosetting polymer system typically created by chemical reaction between epoxy resin and hardener, producing a cross-linked material.

Failure Hierarchy

The intended or observed sequence and location of failure among components of a repaired assembly as loading or deterioration increases.

Flexural Strength

The stress associated with failure of a material subjected to bending under a defined test method.

Fracture Toughness

Resistance to initiation and propagation of a crack, commonly expressed through fracture-mechanics parameters rather than simple ultimate stress.

Freeze-Thaw Cycling

Repeated freezing and thawing of moisture-containing material, potentially contributing to deterioration depending upon saturation, pore structure, and environmental conditions.

Full-Surface Bonding

Continuous or nearly continuous structural adhesive coverage across a large interface.

Geometric Retreatability

The degree to which repair geometry preserves physical access for future dismantling or treatment even where the adhesive itself is chemically irreversible.

Glass-Transition Temperature (T_g)

Temperature range over which an amorphous polymer changes substantially in molecular mobility and mechanical behavior, transitioning between more glassy and more rubbery responses.

Grout

Flowable or injectable material used to fill cracks, voids, or separations and restore contact or continuity. Grout should not automatically be considered equivalent to a structural adhesive.

Hydraulic Lime

Lime binder capable of developing strength through hydraulic reactions with water as well as later carbonation.

Informational Retreatability

The preservation of sufficient treatment documentation that future practitioners can identify and understand concealed interventions.

Injection Grout

Grout formulated to flow or be injected into cracks, voids, delaminations, or inaccessible cavities.

Intervention Layer

A deliberately applied intermediate material, commonly a thermoplastic resin such as B-72, intended to isolate an irreversible adhesive from direct contact with historic substrate and improve future retreatability.

Lead Wedge

Thin wedge or shim of lead used in monument setting for leveling, joint spacing, conformable bearing adjustment, and localized load distribution.

Limited-Bond Reassembly

A treatment strategy in which structural adhesive is deliberately confined to selected locations while stable bearing, geometry, friction, and other components carry the primary normal loads.

Load Path

The route through which structural forces travel from one component to another and ultimately into the foundation or support.

Loss Compensation

Introduction of new material to replace missing volume or visual form without necessarily performing the principal structural bond.

Marble

Metamorphic rock principally composed of recrystallized carbonate minerals, commonly calcite or dolomite.

Mechanical Interlock

Physical resistance to separation created when adhesive engages irregular surface geometry in addition to chemical adhesion.

Mechanical Reinforcement

Pins, dowels, anchors, cramps, rods, or related components that transfer structural loads through mechanical engagement with the stone.

Minimum Intervention

The least permanent alteration capable of achieving the legitimate preservation and safety objective.

Necessary Permanence

An irreversible treatment justified because a less permanent alternative cannot provide comparable preservation, structural capacity, safety, or durability without equal or greater risk.

NHL

Natural hydraulic lime.

Peel

Progressive separation beginning at an edge of an adhesive joint, producing locally concentrated stresses rather than uniform loading across the entire bond.

Perimeter Joint

The exposed outer portion of an interface between monument components.

Pin / Dowel

Mechanical reinforcement inserted into drilled holes to transfer load across a joint or secure an attached element.

Polymer

Large molecular material composed of repeating units; epoxies, acrylics, polyesters, and many sealants are polymeric materials.

Polyester Mastic

Rapid-curing polyester resin system commonly used in commercial stone fabrication for bonding, filling, seaming, and patching.

Reversibility

Degree to which the effects of treatment can be undone without unacceptable alteration or damage to original material.

Retreatability

Practical ability to modify, remove, replace, or work around a previous treatment during future conservation intervention.

Rocking

Alternating rotational movement of a monument component between changing bearing points.

Sacrificial Material

Repair material intentionally selected or designed to deteriorate or fail preferentially before significant loss of the historic substrate.

Service Capacity

Structural capacity required for a repair to remain stable under expected normal conditions with suitable reserve for foreseeable variation.

Setting Compound

Proprietary or traditional material used at monument joints for setting, perimeter closure, and weather management; typically distinguished from high-strength structural adhesive.

Shear

Loading condition in which adjacent parts of a material or joint tend to slide parallel to one another.

Shim

Thin material used to adjust spacing, level, alignment, or bearing.

Solvent Retention

Persistence of solvent within a polymer film or adhesive after apparent drying, potentially altering mechanical properties and glass-transition behavior.

Spalling

Loss of a surface layer or fragment from stone, commonly approximately parallel to the original surface.

Stiffness

Resistance to deformation under load. Elastic modulus is one common quantitative measure of stiffness.

Stone-to-Stone Bearing

Direct compressive load transfer between monument components through their physical contact surfaces.

Structural Adhesive

Adhesive intended to transfer meaningful structural loads between joined components.

Structural Bedding

Material occupying an interface and carrying significant compressive load rather than merely closing the exterior joint.

Sugaring

Granular disintegration of marble characterized by progressive loss of cohesion among mineral grains, commonly associated with weathering and microcracking.

System-Level Sacrificiality

A repair philosophy in which replaceable layers, limited bonding, accessible joints, appropriate bearing, and other design features collectively encourage less damaging deterioration or failure without requiring every individual material to be mechanically weak.

Tensile Strength

Maximum tensile stress sustained under a defined test before failure.

Thermoplastic

Polymer that does not form a permanently cross-linked network and can generally be softened through heat or appropriate solvent.

Thermoset / Thermosetting Polymer

Polymer that develops a chemically cross-linked network during cure and cannot normally be returned to its original uncured condition by solvent.

Thermal Expansion

Change in material dimensions associated with temperature change.

Uplift

Tensile separation force acting to lift one monument component away from another.

Vapor Permeability

Ability of water vapor to move through a material under a vapor-pressure gradient.

Wet-Dry Cycling

Repeated exposure to moisture followed by drying, producing changes in saturation, salts, dimensional behavior, and material condition.

Workability

Period and consistency during which an adhesive, grout, mortar, or putty can be placed and adjusted before setting progresses excessively.

Workmanship

The combination of preparation, proportioning, mixing, placement, alignment, curing, cleanup, and quality control through which a treatment material is converted into a completed repair.

K.2. Closing Note on Terminology

The terminology used throughout Technical Paper No. 3 is intended to reduce several ambiguities common in discussions of monument repair. In particular, **adhesive strength**, **bond strength**, **stone strength**, **stiffness**, and **fracture toughness** should not be used interchangeably. Likewise, **reversibility**, **retreatability**, and **sacrificial failure** describe related but distinct conservation properties.

The distinction between **bearing** and **bonding** is fundamental to the treatment framework developed in the paper. Bearing determines how compression is transferred through a monument; bonding determines how components transmit forces that would otherwise cause relative separation or sliding. Treating these functions as synonymous tends to encourage greater structural adhesive use than many monument configurations actually require.

The terms **limited-bond reassembly**, **failure hierarchy**, **system-level sacrificiality**, **necessary permanence**, and **informational retreatability** are used in this paper as organizing concepts for the proposed Gravestone Guardians treatment philosophy. They should be regarded as defined working terminology rather than claims that these phrases represent universally adopted professional standards.

Appendix L: Literature Review Methodology and Evidence Matrix

L.1 Purpose and Review Design

The literature review supporting *Structural Adhesives in Historic Marble Monument Repair: Strength, Stiffness, Failure Hierarchy, and Limited-Bond Reassembly Systems* was undertaken to establish the scientific, conservation, technical, and practice-based evidence relevant to structural joining of historic marble. The review was designed to answer a problem broader than the conventional question of which adhesive possesses the greatest bond strength. It sought evidence concerning the mechanical behavior of marble-adhesive interfaces; the effects of stone weathering on those interfaces; the relationship among adhesive strength, stiffness, fracture toughness, bond geometry, and failure mode; the conservation concepts of reversibility and retreatability; the performance of intervention layers; the structural implications of pins and dowels; the appropriate roles of mineral grouts and mortars; and the influence of environmental aging upon repaired stone.

The review is best characterized as a **structured narrative review with targeted evidence verification**. It was not conducted as a formal systematic review under PRISMA or an equivalent protocol, and no claim is made that every potentially relevant publication was captured. The literature surrounding stone conservation is distributed across conservation journals, engineering and geoscience publications, specialist postprints, institutional research reports, technical standards, manufacturer literature, cemetery-preservation guidance, and practitioner documentation. A rigid database-only strategy would consequently have excluded several categories of evidence necessary to understand actual monument treatment.

The review instead combined focused searches of scholarly and publisher sources with targeted examination of conservation-institution repositories, standards organizations, government preservation resources, manufacturer technical data, and documented monument-setting practice. Searches and source verification continued through August 7, 2026. No lower publication-date limit was imposed because several foundational publications remain central to present conservation practice, including Appelbaum's 1987 treatment of reversibility, Selwitz's 1992 review of epoxy resins in stone conservation, and the marble-adhesive experiments of Podany and colleagues published in 2001 (Appelbaum, 1987; Podany et al., 2001; Selwitz, 1992).

L.2 Review Questions

Evidence was screened against four principal questions. The first concerned **structural adequacy**: which material and joint properties determine whether an adhesive or reassembly system can provide sufficient capacity for its intended monument configuration? The second concerned **conservation consequence**: when a repaired system is overloaded or deteriorates, does failure occur within the adhesive, at the interface, within the historic marble, around mechanical reinforcement, or elsewhere in the monument? The third concerned **future treatment**: how do permanence, solvent responsiveness, adhesive penetration, bonded area, access, and documentation affect practical retreatability? The fourth concerned **exterior durability**: how do thermal cycling, moisture, salts, ultraviolet exposure, freeze-thaw conditions, creep, and progressive marble weathering alter the behavior of the repaired assembly?

These questions deliberately required consideration of the repair system rather than the adhesive alone. Research on marble-adhesive interfaces establishes that thermosetting and thermoplastic adhesives can both become sufficiently strong for cohesive failure to occur in marble, while fracture-mechanics studies demonstrate the importance of interface geometry and mode of loading. Research on granite further shows that intervention layers can improve reversibility while simultaneously affecting water transport. Such findings make it inappropriate to infer conservation performance from one bulk material property (Alonso-Villar et al., 2019; Podany et al., 2001; Rahbar et al., 2010).

L.3 Search Strategy

Searches were iterative rather than limited to one predefined query. Initial searches concentrated upon broad combinations of terms such as *marble adhesive conservation*, *structural adhesive marble repair*, *epoxy stone conservation*, *thermoplastic adhesive marble*, *Paraloid B-72 structural adhesive*, *adhesive fracture toughness marble*, and *reversibility stone adhesive*. References identified within the strongest directly relevant publications were then used to expand the review into related mechanical and conservation subjects.

Subsequent searches examined *marble thermal weathering*, *calcite anisotropic thermal expansion*, *marble microcracking*, *ultrasonic marble deterioration*, *adhesive intervention layer*, *B-72 residual solvent*, *outdoor polymer stone weathering*, *marble pinning materials*, *stone dowel modulus*, *lime injection grout conservation*, *mineral grout stone repair*, *salt crystallization natural stone*, *freeze-thaw natural stone*, *lead monument setting*, and *monument setting compound*. Product-specific searches were conducted for AKEPOX 5010, Akepox 2000, Tenax Domo 10, Tenax Elix, HXTAL NYL-1, EPO-TEK 301-2, Pratley

Standard Setting Putty and related Pratley products, Paraloid B-72 and B-48N, Heritage IG10, Marmorkitt and representative polyester mastics.

Where a manufacturer technical data sheet was available, it was preferred over reseller descriptions for quantitative product claims. Reseller or practitioner pages were retained only where they documented field practice not stated in the technical sheet—for example, the combined use of localized Pratley Putty, lead wedge, and monument setting compound in flat-base monument reassembly. Institutional specifications were preferred over informal descriptions where both were available. The Town of Nantucket's Old North Cemetery conservation specification, for example, independently documents the use of bonding agent, lead wedges, and monument setting compound for detached markers (Atlas Preservation, n.d.-a; Town of Nantucket, 2022).

L.4 Inclusion and Exclusion Criteria

Sources were included when they met at least one of the following conditions: they presented direct experimental evidence on marble or stone adhesives; they examined physical deterioration mechanisms relevant to historic marble; they addressed adhesive fracture, intervention layers, reversibility, or structural reinforcement; they provided formal conservation methodology for grout or stone testing; they represented current professional standards or government preservation guidance; they contained primary manufacturer specifications necessary to characterize a material actually considered in the manuscript; or they documented a monument-repair configuration relevant to the Gravestone Guardians limited-bond hypothesis.

Preference was given to original research rather than derivative summaries. Peer-reviewed journal publications were preferred for scientific conclusions. Formal conservation research reports and specialist postprints were retained where they represented unusually direct evidence even when formal peer review was absent. This distinction is important for the Jorjani and Riccardelli studies published through the AIC Objects Specialty Group: both provide unusually relevant experimental evidence, but Objects Specialty Group Postprints explicitly states that its papers are edited for clarity and content rather than subjected to formal peer review. Their findings are therefore treated as important conservation research without mischaracterizing their publication status (Jorjani et al., 2008; Riccardelli et al., 2010).

Sources were excluded or given little evidentiary weight when they consisted solely of anonymous forum discussion, unsupported promotional claims, duplicated reseller descriptions where primary manufacturer information was available, or materials whose relationship to historic stone could not be established. Research on non-stone substrates

was retained only when it addressed a material phenomenon directly relevant to the paper and no more suitable stone-specific evidence was available.

The review also rejected inappropriate numerical comparison. Mechanical figures obtained using different substrates and test standards were not treated as directly interchangeable. A bulk tensile-strength value for cured epoxy, for example, was not equated with an adhesive pull-off value, stone flexural strength, lap-shear result, fracture toughness, or grout bond-strength test. ASTM methods were used to understand test architecture and terminology rather than to imply that tests designed for metals, concrete, or dimension stone automatically reproduce weathered historic-marble behavior.

L.5 Evidence Hierarchy

Evidence was classified into five tiers. The hierarchy reflects the type of claim each source can support rather than assigning a universal measure of source quality.

Table L. 1: Evidence Hierarchy for the Literature Review

Tier	Evidence Class	Appropriate Use in This Paper	Principal Limitation
Tier 1	Peer-reviewed experimental or analytical research directly relevant to marble, stone adhesives, stone deterioration, or exterior polymer behavior	Principal support for mechanical mechanisms, failure behavior, weathering, hydric effects, and material aging	Laboratory substrates and geometry may not reproduce cemetery conditions
Tier 2	Formal conservation research monographs, technical reports, edited specialist proceedings, and conservation experiments not subjected to conventional journal peer review	Direct specialist evidence, historical treatment research, experimental precedents, development of conservation-specific methods	Publication review process varies; results may derive from museum rather than exterior applications
Tier 3	Professional ethics, institutional guidance, government conservation	Professional principles, documentation standards, treatment	Generally does not prove comparative performance of a particular adhesive on

Tier	Evidence Class	Appropriate Use in This Paper	Principal Limitation
	publications, ASTM or comparable test standards	planning, methodological frameworks, standardized test terminology	historic marble
Tier 4	Manufacturer technical data sheets and primary manufacturer product documentation	Composition, mix ratio, working time, cure, reported mechanical properties, intended substrate, environmental limitations	Manufacturer testing is product-oriented and does not establish conservation suitability or superiority
Tier 5	Practitioner documentation, cemetery specifications, training resources, and commercial preservation-system descriptions	Evidence that a method exists in field practice; formulation of testable hypotheses; identification of common setting configurations	Not controlled scientific validation; recommendations may reflect practitioner or commercial preference

The hierarchy is **claim-specific**. A Tier 4 manufacturer data sheet is the strongest available source for the manufacturer's prescribed 2:1 mixing ratio of Akepox 5010, whereas a manufacturer statement that a product creates an exceptionally strong bond is not sufficient evidence that the product is preferable for weathered historic marble. Conversely, a peer-reviewed adhesive experiment may establish fracture behavior while providing no reliable guidance regarding a current manufacturer's formulation or cure instructions.

L.6 Directness and Transferability

A second classification was applied independently of source tier because high-quality research can still be only indirectly transferable to cemetery monuments.

Direct evidence included experimental work involving marble-adhesive interfaces, marble pinning, or physical deterioration of marble. **Near-direct evidence** included experimental work on other natural stones, exterior stone polymers, conservation grouts, or related heritage substrates whose mechanisms were relevant but whose substrate differed from marble. **Indirect evidence** included general standards, product specifications, architectural guidance, and field-practice descriptions.

This distinction prevents several common errors of extrapolation. Findings obtained from granite were not assumed to describe marble quantitatively. Results from fresh Carrara marble were not assumed to reproduce severely weathered cemetery marble. Polymer behavior observed in indoor collection environments was not automatically treated as exterior service performance. ASTM tests for new dimension stone were not used as substitutes for characterization of historic gravestones. Likewise, mineral composition was not treated as evidence that a grout would necessarily be mechanically weaker or more sacrificial than an epoxy.

The intervention-layer literature illustrates why this distinction is necessary. Podany and colleagues directly tested B-72 barriers within structural adhesive bonds on marble and found substantially improved reversibility without eliminating cohesive marble failure. Alonso-Villar and colleagues later found that a B-72 intervention layer improved reversibility on granite but also acted as a barrier to water transport. The first study is direct evidence for marble structural behavior; the second is near-direct evidence that raises an important hydric concern requiring marble-specific verification rather than direct quantitative transfer (Alonso-Villar et al., 2019; Podany et al., 2001).

L.7 Evidence Extraction

For each major source, the following information was extracted where available: substrate; adhesive, grout, reinforcement, or treatment system; test or evaluation method; environmental conditioning; mechanical properties evaluated; location and character of failure; reversibility or retreatability observations; moisture or color effects; relevance to monument repair; and significant limitations affecting transferability.

Manufacturer sources were extracted differently. Fields included material type, mixing ratio, viscosity or consistency, working time, cure requirements, environmental limitations, reported mechanical properties, moisture tolerance, UV or yellowing information, removal limitations, and stated intended use. Manufacturer claims were retained as **reported properties** rather than converted into independent conservation conclusions.

Practice sources were used to extract configuration rather than performance. For example, Atlas Preservation documents a repair kit combining monument setting compound, Pratley Standard Setting Putty, and lead wedge, and its published guidance places Pratley at interior contact points while setting compound is used around the exterior. This is valuable evidence that such functional separation exists in contemporary monument practice, but it does not demonstrate that the arrangement has a superior failure hierarchy (Atlas Preservation, n.d.-a).

L.8 Synthesis Method

Because the studies differed substantially in substrate condition, adhesive formulation, joint geometry, loading, test method, and environmental conditioning, no attempt was made to calculate pooled effect sizes or rank materials through meta-analysis. The evidence was synthesized thematically around the mechanical and conservation questions developed in the body of the paper.

The principal synthesis themes were: substrate deterioration; adhesive strength and stiffness; fracture toughness; joint geometry and bond area; cohesive versus adhesive failure; thermoset permanence; thermoplastic reversibility; intervention layers; moisture transport; environmental aging; pin and dowel mechanics; mineral grouts and mortars; bearing and restraint; and treatment documentation. Conflicting findings were not averaged into a single conclusion but examined for differences in substrate, geometry, and test conditions that could explain the disagreement.

The review deliberately distinguishes **absence of evidence from evidence of absence**. For example, the lack of published marble-specific modulus and fracture-toughness data for Pratley Standard Setting Putty does not demonstrate poor performance; it prevents a strong material-specific claim. The GG limited-bond system is consequently presented as a mechanically plausible and practice-supported hypothesis requiring experimental validation rather than as an established scientifically demonstrated superior treatment.

L.9 Calibration of Manuscript Claims

To prevent the discussion from becoming more certain than the underlying evidence permits, conclusions should be read according to four evidentiary levels:

Table L.2: Manuscript Claim Levels and Evidentiary Meaning

Claim Level	Meaning
Established	Supported directly by strong experimental or professional evidence and, where appropriate, corroborated by multiple sources
Supported	Consistent with direct evidence but subject to meaningful limitations in substrate, geometry, or environmental transferability
Provisional	Mechanically or chemically plausible and supported indirectly, but lacking direct validation for the precise historic-marble application
Research hypothesis	Proposed by this paper or derived from GG field practice and requiring dedicated testing before general adoption

Examples clarify the distinction. The anisotropic thermal expansion of calcite and its contribution to marble microcracking are **established** within the stone-weathering literature (Siegesmund et al., 2000). The conclusion that B-72 intervention layers can

improve deliberate reversibility of marble structural bonds is likewise strongly supported by direct testing (Podany et al., 2001). The assertion that such layers will provide the same benefit beneath AKEPOX 5010 on weathered exterior cemetery marble is **provisional**, because that precise combination and environment have not been established in the located literature. The proposition that stable bearing plus deliberately limited Pratley restraint will reduce original-stone loss relative to full-area bonding or unnecessary pinning is a **research hypothesis** that Chapters 21–24 are designed to test.

L.10 Treatment of Manufacturer and Practitioner Evidence

Manufacturer literature was deliberately retained because an adhesive paper cannot characterize current commercial products responsibly without referring to the entities that formulate them. AKEPOX 5010's technical sheet, for example, provides the product's mixing ratio, tensile and flexural strength, temperature-dependent working time, low-shrinkage characterization, weather resistance, and statement that cured material cannot be removed with solvent. These are appropriate manufacturer-supported facts (AKEMI GmbH, 2022).

The same restraint applies to Tenax Domo 10. Tenax identifies the product as a permanent structural epoxy suitable for exterior and damp-surface bonding and markets the adhesive on the basis of extremely high bond performance. Its 2023 technical data sheet additionally reports high yellowing in the listed Q-Sun climatic-chamber exposure. Those observations legitimately inform comparison of product characteristics; they do not establish that Domo 10 is either conservation-inappropriate or superior to AKEPOX 5010 (Tenax S.p.A., 2023; Tenax USA, n.d.-b).

Practice evidence was used still more narrowly. The Nantucket specification, Atlas Preservation documentation, and Cemetery Conservators for United Standards guidance demonstrate that combinations of lead spacers, mortar or setting compound, and bonding materials occur in contemporary cemetery-preservation practice (Town of Nantucket, 2022). These sources help establish practical context and identify systems worth testing. They do not replace controlled mechanical evaluation (Atlas Preservation, n.d.-a; Cemetery Conservators for United Standards, n.d.; Town of Nantucket, 2022).

L.11 Limitations of the Review

Several limitations should remain explicit. The first is that this was not an exhaustive systematic database review, and the literature base almost certainly contains additional relevant studies. The second is the relative scarcity of experimental research reproducing naturally weathered cemetery marble, large monument components, full exterior exposure, and decades of treatment aging. Most direct adhesive research has been

performed with comparatively sound marble specimens under controlled laboratory conditions.

A third limitation is that product formulations can change. Manufacturer data recorded in this paper describe documentation available during preparation of the report and should be rechecked before future field use or experimental work. A fourth is that some influential conservation evidence appears in specialist postprints or institutional reports rather than peer-reviewed journals. Such evidence has been retained because of its unusually direct relevance but identified according to publication type.

Finally, the review necessarily combines evidence created for different purposes. An engineering fracture test, a conservation ethics statement, a manufacturer data sheet, and a municipal cemetery specification answer different questions. The evidence hierarchy and matrix are intended precisely to prevent those sources from being treated as though they were equivalent.

L.12 Updating the Review

Because Technical Paper No. 3 proposes an experimental research agenda rather than a closed material specification, Appendix L should be treated as a living component of future editions. Newly published marble-adhesive studies, formulation changes, long-term field observations, laboratory results produced through the proposed GG experimental program, and documented treatment failures should be incorporated in subsequent revisions.

Future updates should retain a source even when its conclusions are unfavorable to current Gravestone Guardians practice. Negative evidence concerning AKEPOX 5010, Pratley Putty, intervention layers, lead, mineral grout, or the limited-bond system is not contrary to the purpose of the paper. It is precisely the evidence needed to determine the boundaries within which those treatments remain defensible.

Table L.3: Core Evidence-Screening and Extraction Matrix

Source	Tier / Directness	System or Substrate	Evidence Extracted	Principal Limitation	Use in TP3
Appelbaum (1987)	Tier 1; conceptual conservation evidence	Conservation treatments generally	Reversibility is a property of a treatment process rather than simply a soluble material; reversibility exists in degrees; future re-treatability should be considered	Not specific to stone mechanics	Foundation for distinction among reversibility, retreatability, and permanence (Appelbaum, 1987).
Selwitz (1992)	Tier 2; near-direct	Epoxy systems in stone conservation	Epoxies constitute a broad material family; performance depends on formulation, penetration, yellowing, water behavior, and application; exceptional strengthening can be both useful and problematic	Primarily review/monograph; much literature predates current adhesives	Historical and chemical framework for epoxy discussion (Selwitz, 1992).
Podany et al. (2001)	Tier 1; direct	Marble bonded with epoxy, polyester, B-72, and B-72 intervention-layer systems	B-72 can provide significant structural capacity; many specimens failed within marble; intervention layer markedly improved reversibility without necessarily forcing adhesive failure	Controlled marble specimens; museum/sculpture context rather than cemetery exposure	Central evidence for failure hierarchy and intervention layers (Podany et al., 2001).
Jorjani et al. (2008)	Tier 2; direct; edited but not formally peer reviewed	Carrara marble; B-72, B-48N, HXTAL, Epo-Tek, Akepox 2000, polyester and layered systems	Thermoplastic and thermosetting systems overlapped in fracture-toughness performance; all tested systems could provide adequate marble bonding; joint width and fracture mechanics important	Laboratory Carrara marble; specialist postprint; not formal peer review	Supports moving beyond tensile-strength-only selection
Rahbar et al. (2010)	Tier 1; direct	Marble/adhesive interfaces	Mixed-mode fracture toughness varies with loading mode and interface behavior; crack mechanics are central to joint robustness	Controlled specimen geometry	Supports emphasis on fracture toughness, joint geometry, and load direction (Rahbar et al., 2010).

Table L.3: Core Evidence-Screening and Extraction Matrix

Source	Tier / Directness	System or Substrate	Evidence Extracted	Principal Limitation	Use in TP3
Riccardelli et al. (2010)	Tier 2; direct; edited but not formally peer reviewed	Carrara marble cores with different pin materials	Pin modulus and material affect failure; some lower-modulus fiber systems provided sufficient capacity while reducing stone damage relative to stiff metals in tested configuration	Museum-sculpture context; particular pin geometry; not formal peer review	Supports nuanced discussion of pin stiffness and failure hierarchy (Riccardelli et al., 2010).
Siegesmund et al. (2000)	Tier 1; direct to marble substrate	Multiple marble types	Calcite thermal anisotropy and stone fabric drive microcracking and progressive cohesion loss; marble response varies by texture	Thermal-weathering study, not adhesive study	Establishes why weathered marble differs mechanically from new laboratory stone (Siegesmund et al., 2000).
Leiss & Weiss (2000)	Tier 1; direct to marble substrate	Carrara marble varieties	Texture, grain size, shape, grain boundaries, and microcracking alter thermally induced degradation	High-temperature laboratory work exceeds normal service range	Supports substrate anisotropy and variability discussion (Leiss & Weiss, 2000).
Siegesmund, Menningen, & Shushakova (2021)	Tier 1; direct to marble substrate	Weathered and experimentally treated marble	Ultrasonic wave velocity is sensitive to degradation and can track microcracking and loss of elastic performance	Does not evaluate adhesives	Basis for marble characterization and proposed nondestructive experimental monitoring (Siegesmund et al., 2021).
Vinçotte et al. (2019)	Tier 1; direct to acrylic material	Paraloid B-72 and B-44 films in multiple solvents	Residual solvent can remain for extended periods and substantially depress glass-transition temperature	Polymer-film study rather than stone joint	Supports caution regarding B-72 drying, creep, and intervention-layer cure (Vinçotte et al., 2019).
Alonso-Villar, Rivas, & Pozo-Antonio (2019)	Tier 1; near-direct	Granite with epoxy/acrylic adhesives and B-72 intervention layers	B-72 improved reversibility but affected water transport; high adhesion could still produce rock failure	Granite rather than marble	Supports hydric caution surrounding intervention layers and distinction between reversibility and sacrificial failure (Alonso-Villar et al., 2019).
Favaro et al. (2006)	Tier 1; near-direct	Conservation polymers applied to marble and	Photo-oxidative exposure changes polymer properties and	Coating/consolidation rather than structural joints	Supports environmental-aging and UV protocols

Table L.3: Core Evidence-Screening and Extraction Matrix

Source	Tier / Directness	System or Substrate	Evidence Extracted	Principal Limitation	Use in TP3
		artificially weathered	removability; exterior behavior must be examined beyond initial cure		(Favaro et al., 2006).
Favaro et al. (2007)	Tier 1; near-direct	Acrylic-silicone treatment on marble	Combined light/salt exposure produces chemical and conservation-performance changes; field observations can corroborate accelerated aging	Treatment mixture differs from structural adhesives in TP3	Supports modular environmental aging and caution regarding accelerated tests (Favaro et al., 2007).
Biçer-Şimşir et al. (2009)	Tier 1/2; near-direct	Lime and hydraulic injection grouts for heritage surfaces	Grout compatibility requires consideration of injectability, shrinkage, strength, porosity, and substrate interaction rather than binder identity alone	Architectural surfaces rather than structural marble fractures	Supports differentiation of grout from structural adhesive (Biçer-Şimşir et al., 2009).
Biçer-Şimşir & Rainer (2013)	Tier 2; near-direct	Conservation injection grouts	Existing conventional test standards often require adaptation for conservation materials; provides laboratory/field procedures	Focuses on plaster/mosaic and architectural surfaces	Methodological precedent for conservation-specific adaptation of standard tests (Biçer-Şimşir & Rainer, 2013).
Lisci et al. (2022)	Tier 1; indirect/near-direct	Natural limestone under salt crystallization	Modified EN 12370 procedure illustrates value of more realistic salt concentration and drying temperatures; deterioration can be tracked using multiple physical/mechanical indicators	Limestone rather than marble and no adhesive	Supports environmental-aging design and rejection of uncritical “torture tests” (Lisci et al., 2022).
Arizzi & Parra-Fernández (2025)	Tier 1; near-direct	Natural hydraulic limes	NHL classification alone does not define finished material properties; nominally similar NHL grades can differ materially	Review of lime manufacture, not monument adhesives	Supports treatment of NHL as variable material family rather than uniform “compatible” mortar (Arizzi & Parra-Fernández, 2025).

Table L.4: Standards, Institutional Guidance, Product Data, and Practice Evidence

Source	Tier	Evidence Used	Limitation / Interpretation
AIC Code of Ethics and Guidelines for Practice	3	Examination before treatment; suitability; balancing treatment benefits and future effects; documentation; nonintervention can be appropriate	Ethical/professional framework, not product validation
NPS Preservation Brief 48	3	Cemetery condition assessment, material identification, causes of deterioration, appropriate preservation treatment	Broad cemetery guidance rather than comparative adhesive mechanics (Gale et al., 2016).
NPS cemetery documentation guidance	3	Written and photographic documentation, recurring assessment, recording previous repair and conditions	Supports treatment-management framework rather than adhesive selection
ASTM D2095	3	Reference framework for tensile testing of bonded specimens	General adhesive test; historic-marble adaptation required
ASTM D1002	3	Reference framework for shear-testing concepts	Developed for adhesively bonded metals; not direct stone-conservation test
ASTM C880/C880M	3	Flexural-test concepts for dimension stone	New dimension stone rather than deteriorated grave markers
AKEPOX 5010 TDS	4	Product chemistry, 2:1 ratio, working/cure time, reported tensile/flexural properties, low shrinkage, exterior behavior, irreversible cured condition	Manufacturer product testing; cannot establish conservation superiority
Tenax Domo 10 TDS/product	4	1:1 ratio, thixotropic epoxy, exterior/damp	Manufacturer evidence; fabrication priorities differ

Source	Tier	Evidence Used	Limitation / Interpretation
documentation		use, permanent high-strength design, Shore D data, high reported Q-Sun yellowing	from conservation priorities (Tenax USA, n.d.-b).
HXTAL NYL-1 technical sheet	4	Conservation origin, 3:1 mix, tensile strength/modulus, elongation, flexural properties, optical aging, heat-distortion data	Manufacturer values; does not demonstrate routine exterior-monument suitability
EPO-TEK 301-2 technical documentation	4	Low viscosity, optical epoxy characteristics, working/cure information, mechanical benchmarks	Specialized industrial product; field monument transfer requires justification (Epoxy Technology, Inc., n.d.).
Pratley Standard Setting Putty instructions	4	Epoxy putty, equal-part mixing, working/set times, hard cure, wet/underwater capability	Public technical literature lacks complete modulus/fracture-toughness data needed for direct conservation comparison
Dow Paraloid B-72/B-48N documentation	4	Polymer identity and commercial material characteristics	Manufacturer pages supplement, but do not replace, independent conservation research
Heritage IG10 technical data	4	Cementitious formulation, crack/void use, reported compressive, flexural, bond, modulus, porosity, and absorption properties	Manufacturer data; strength values from different tests cannot be compared directly with epoxy tensile strength
Town of Nantucket Old North Cemetery specification	5/Institutional specification	Detached marker resetting with bonding agent, lead wedges, and monument setting compound; epoxy/lime-mortar treatment combinations	Demonstrates specified practice, not comparative scientific validation (Town of Nantucket, 2022).
Atlas	5	Combined use of Pratley	Commercial/practitioner

Source	Tier	Evidence Used	Limitation / Interpretation
Preservation monument repair system		Putty, lead wedge, and monument setting compound; interior structural adhesive/perimeter-setting distinction	evidence; useful for documenting practice rather than proving efficacy (Atlas Preservation, n.d.-a).
Cemetery Conservators for United Standards	5	Gravity-dependent multi-piece monument construction, lead spacers, mortar/setting techniques	Practitioner-developed guidance rather than formal standard or experimental research (Cemetery Conservators for United Standards, n.d.).

L.13 Evidence Gaps Identified Through the Review

The evidence matrix reveals several gaps that are more consequential than the absence of another product comparison. No located study directly compares full-area bonding, deliberately limited adhesive pads, stable bearing, lead wedges, and mechanical pinning using otherwise comparable weathered marble monument mock-ups. Likewise, no direct published study was identified that evaluates Pratley Standard Setting Putty as a limited-area structural restraint on weathered marble or quantifies the consequences of varying Pratley pad area and location.

Evidence concerning AKEPOX 5010 is stronger at the manufacturer-property and field-practice levels than at the independent historic-marble experimental level. Related Akepox formulations have appeared in conservation testing, but the precise GG use of 5010 on exterior weathered tablet fractures requires dedicated validation. The same applies to B-72 used beneath 5010 or beneath localized Pratley: the intervention-layer principle is well supported, but the specific combinations and exterior environment remain untested in the literature identified here.

Existing research also provides little direct information on how these repair systems change after realistic combinations of thermal cycling, moisture, freeze-thaw exposure, and sustained structural loading. Research on polymer weathering, marble deterioration, and salt cycling provides mechanisms and experimental precedents, but the complete repaired monument remains underrepresented.

These gaps explain why Chapters 21–24 emphasize **system-level experimental work, environmental aging, quantification of original-stone loss, and post-aging**

retreatability rather than another simple adhesive tensile test. The evidence base is already sufficient to establish that multiple adhesive classes can hold marble. The less well answered question is which configuration preserves the greatest amount of historic material over the complete life cycle of the repair.

L.14 Reference List Note

The reference list is presented in a single alphabetical sequence to maintain a coherent APA 7 author–date system. Appendix L retains the evidentiary classification of peer-reviewed research, specialist conservation literature, institutional guidance, manufacturer technical data, and practitioner evidence so that source type and evidentiary weight remain transparent without fragmenting the reference list itself.

Inclusion of a commercial, manufacturer, or practitioner source does not assign it the evidentiary weight of peer-reviewed research. Such sources are cited only for claims they are positioned to support, including product formulation and instructions, current specifications, or documented field practice. Scholarly publication likewise does not eliminate questions of transferability: studies using fresh Carrara marble, granite, museum objects, or polymer films provide evidence about mechanisms but do not by themselves validate treatment of severely weathered exterior cemetery marble.

The reference list should be reviewed in future editions whenever a product formulation changes, a source is superseded, or new independent experimental research materially changes the treatment framework. Results from the proposed Gravestone Guardians experimental program should be incorporated under the same standards of traceability, claim-specific citation, and evidentiary transparency.

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