Waste materials: A study of their potential contribution to sustainable construction

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ABSTRACT: Research interest in recycled and renewable materials has been created out of concern that future generations will not have the thriving world we take for granted. Therefore, it is imperative that additional research into sustainable building and design practices is conducted to ensure this does not occur. A review of the literature indicates that innovation in this area is mostly limited to experimental concrete aggregates. This paper expands on the literature by asking *can waste materials provide alternatives to contemporary materials in the construction industry?* To answer this primary research question, three case studies are undertaken to understand how waste materials are innovatively used in contemporary dwelling construction. The case studies found that there are innovative approaches to using waste materials in construction but these are introduced in a disorganised way. This paper suggests that changes in materials uses are driven by technology and that wider acceptance of this will depend on the costs involved and the extent of BCA approval. It is recommended that more support is needed to bring innovative ideas into mainstream use. This paper also proposes that architects, designers and builders need to overcome problems with inflexible thinking in terms of using waste materials. There is a need for a paradigm shift towards thinking about how much of these materials could be used in construction as alternatives to current conventional materials.

Keywords: Waste material, construction and demolition, recycling, alternative materials

INTRODUCTION

Throughout the 21st century there has increasing concern about global warming, greenhouse gases, finite non-renewable resources and the growing population. These issues are affected by the built environment, how designers and architects design, and the materials that are chosen for structural and aesthetic reasons. The use of non-renewable resources in the construction industry is a notable contributor to the depletion of valuable resources and therefore research into material alternatives is paramount.

Construction and demolition (C&D) waste constitutes 42% of all landfills in Australia (Australian Bureau of Statistics, 2010). In addition, landfills are becoming increasingly full and this has led to them becoming tightly compacted waste. When biodegradable waste is compacted to the extent of modern landfills, the natural biodegrading process is hindered and this can create environmental problems with the production of by-products such as carbon dioxide and methane gases (Levis & Barlaz, 2011). The use of non-renewable resources, the increasing landfill from waste and associated environmental problems warrants an investigation of how the construction industry can contribute to reducing these problems.

Hence, the aim of this research is to investigate the potential uses of waste materials in the construction industry and to identify the barriers that currently prevent the integration of these materials into contemporary mainstream construction. The following primary research question is proposed: *Can waste materials provide alternatives to contemporary materials in the construction industry?*

The specific objectives of this dissertation are to identify:

1. What waste materials are available and in what quantities

2. Why waste materials should be included in construction

3. Which specific waste materials are suitable for use in construction.

4. The barriers that prevent greater use of waste materials in contemporary dwelling construction?

5. How waste materials can be incorporated into contemporary dwelling construction?

This paper focuses on manufacturing, societal and C&D waste and only those materials that can be used in the construction industry. As the issue of material waste is a global problem, this paper will start by looking at material waste in a world wide sense, then narrowing its scope to how waste can be used in the Australian construction industry where possible.

It should be noted that there is a large amount of literature on the chemistry and physics of waste materials, but analysis of this is outside the scope of this paper. Therefore, the research will be confined to an investigation of how the use of waste materials can be increased in mainstream construction, rather than their chemical properties. Finally, this paper only considers small scale residential and commercial construction because it lends itself to the use of more experimental waste material alternatives.

1. Methodology

The research for this paper will be undertaken through a literature review which will identify the types of waste materials available (Research Objective 1); why waste materials should be included in construction (Research Objective 2); which materials are suitable for use in construction (Research Objective 3); and what barriers prevent the use of these materials in contemporary dwelling construction (Research Objective 4); This will be followed by three case studies which will investigate how waste materials can be used as alternatives to traditional materials in construction, thus addressing Research Objective 5.

2. Definitions

For the purpose of this paper some common terms need to be defined.

Recycling. Refers to a complex variety of processes that transform waste materials into useful materials. This can involve collecting materials, separating and processing them both physically and chemically. It must be said that the recycling process of some materials consumes large amounts of energy (Baetz & Neebe, 1994) so the environmental benefits commonly assumed in recycling do not always eventuate.

Down-cycling. Refers to waste material that has been recycled only once into a material of lesser value. Waste products or by-products can be down-cycled to have more functional use in construction, for example fly-ash, a by-product of refining coal, can be down-cycled and used as an aggregate in concrete. Unlike recycling, there is very little additional energy or resources used in the down-cycling to prepare the material for its new use.

Embodied energy value. Refers to an equation that measures the sum of energy required to obtain, extract or harvest a raw material, manufacture and/or fabricate this material into a useable form, transport it and in some cases its installation (Meryman, 2005). The most intensive use of embodied energy, by area, is in the manufacturing of aluminium and copper (Haynes, 2010). However, it must be noted that recycled forms of these products have significantly less embodied energy than their non-recycled counterparts.

Construction and Demolition (C&D) waste. Any waste material that is excess in the construction process as well as materials that have been deemed obsolete. Demolition waste refers to similar waste materials as construction waste, however these are expressly unused and usually of lesser quality.

Waste materials. Refers to waste materials or products that can be recycled and/or down-cycled for use in construction. This relates to aluminium cans, glass bottles, car tyres, aggregate substitutes, such as, plastics and fibrous materials including paper and cardboard. Some of this material also constitutes C&D waste.

Finite materials. These are materials that come from the earth and which cannot be returned or re-used (CSIRO, 2009).They are also known as non-renewable materials and consist of mostly mined materials such as crude oil, various ores and coal. Once processed, it is impossible for these materials to return to their virgin state.

3. Paper structure

Firstly, this paper reviews the current literature on manufacturing, societal and C&D waste. This includes the identification of waste materials that are suitable for use in construction. Secondly, three case studies are used to explore the integration of recycled and waste materials in dwelling construction. The case studies also identify some of the barriers preventing wider use of waste materials. Finally, recommendations on how an increased use of waste materials can be encouraged in mainstream dwelling construction are provided. A review of the literature is presented in the next section.

4. Literature Review

The aim of this section is to examine the literature on waste material use in construction.

4.1 Objective 1: What waste materials are available and in what quantities

A study of material waste generated from a construction site in the United Arab Emirates, found that one of the major barriers to waste minimisation lies in the increasing amounts of waste material being generated (Al-Hajj & Hamani, 2011). The authors found that contractor's attitudes toward the benefits of material waste minimisation were as a cost-cutting activity not necessarily for the benefit of the environment. Additionally it was found that the environmental aspects of construction waste management are currently neglected by the companies involved in the study (Al-Hajj & Hamani, 2011).

Rajput, Shelar, Gawade& Bhoite (2012) found that the percentage of wastage for cement, fine aggregate, coarse aggregate, and steel in the construction industry accounted for 4.53%, 6.85%, 4.79% and 6.19% respectively. They suggest that the percentage of waste material is likely to be much higher than that found in their single study and that a reduction in wastage can increase profit margins. The authors also highlight the need for better management of waste. In general, the control systems of the construction industry need to be improved so that it becomes easier to reduce or eliminate material waste (Rajput, Shelar, Gawade & Bhoite, 2012).

Yaun (2012) has addressed this problem to some extent. Like Rajput et al. (2012), Yuan believes that most research efforts have been focused on the economic performance of construction waste management while less attention has been paid to investigating the social impact of C&D waste. Yuan's (2012) System Dynamic Model utilises an approach to managing waste which includes among other things, causal loop diagrams and stock-flow diagrams. Yaun's (2012) study is an indication that the construction industry is becoming more conscious of the need for change.

The new European Union challenge is to recover 70% by weight of C&D waste in 2020 (Llatas, 2011). One major barrier to this is the lack of data surrounding the recovery of construction and demolition waste. Llatas (2011) proposes a model which allows technicians to estimate construction and demolition waste during the design stage. This approach increases the chances of recovering C&D waste well above current targets.

As construction and demolition accounts for 45% of the total quantity of solid waste, it is encouraging that there has been a growing interest in the recycling of C&D waste. Most of the research on recycling C&D waste as a potential source of usable materials is largely based on traditional economic analyses, which generally do not attempt to find harmony between economic benefit and environmental effects. According to Yuan, Shen & Li (2011) there is a need for a new strategic approach to the management and use of C&D waste to achieve the integration between economic, social, environmental, and sustainable effects.

Zhang, Wu & Shen (2012) propose that there are various low waste technologies available for construction projects across different stages, including planning and design, construction and operation and maintenance of buildings. Major low waste technologies include:

- Waste sorting/segregation technologies
- Design for reducing foundation size
- Design for reusing excavated spoils as back-fill material to balance cut and fill
- Modular building designs and prefabricated components
- Reuse technology for construction waste (i.e., bricks and tiles)
- Design for recycled materials such as recycled aggregates and asphalt
- Deconstruction or sequential demolition technology
- Use of large panel formwork, Design for hanging cradles

- Design for thinner internal walls and floor slabs

Zhang, Wu & Shen, 2012)

These researchers also suggest that there is a need for policy and regulations to promote the use of low waste technology and to encourage contractors to be more proactive in waste management. Overall, there needs to be more emphasis on waste management plans and environmentally friendly policies when assessing a project's environmental performance. (Zhang, Wu & Shen, 2012)

In summary, there is an increasing amount of material waste in construction with currently no effective or systematic solution to reduce its negative impact on the environment. One positive however, is that the current situation provides scope and ample materials for experimentation to find alternative functions for waste materials, and to assist in the creation of potential new materials.

4.2 Objective 2: Why waste materials should be included in construction?

There has been a shift in how Western society views waste. In Australia, local municipalities provide homes with a recyclable waste collection service and these initiatives have been accompanied by an increasingly environmentally conscious generation that understands the importance of recycling materials. This shift in perspective is also beginning to occur in the construction industry. In 2010, the amount of material reused from construction waste increased beyond the 67% target for that year to 80%, the target for 2013-14.

There are three main reasons why waste materials should be used in construction:

- Waste management issues
- Finding lower embodied energy alternatives
- Decreasing the use of finite materials

Waste management issues. Finding different uses for the waste produced by a growing population will decrease the size of landfills and significantly reduce the need for expansive waste management services in the future.

Lower embodied energy alternatives. Some construction materials that are in constant use in the construction industry have a significant embodied energy value, such as steel, Portland cement and so forth. However, their recycled form does not necessarily reduce their embodied energy value. In contrast, some recycled products like aluminium, have a significant drop in embodied energy when it is recycled (Haynes, 2010). New producers such as GroCon, a construction firm that uses recycled concrete, are an example of the building industry's successful attempt to produce lower embodied energy alternatives.

Decreasing the use of finite materials. If more materials can be re-used, recycled and down-cycled in construction, it will decrease the use of finite materials such as crude oil, iron ore, coal, and perhaps lead the way for other industries to follow suit.

Public and private attempts to reduce waste. Alterman (2005) presents some useful suggestions for using reclaimed and recycled construction materials in dwelling construction and renovation projects. She recommends web sites that offer services for people who want to trade things locally; to find used building materials; and learn techniques for reducing, reusing and recycling when building or remodelling a home. It is evident in this study that there is quite a demand for recycled materials which can result in large cost savings and reduction in the use of finite materials. This is also found with websites such as Ecospecify.com, a product search engine that contains 117 green product categories and 600 sub categories with over 6000 products that meet Australian and international standards (Ecospecifier, 2012)

Australian Government policy has also made an attempt to reduce waste but has not addressed it's potential and actual use in construction. According to the DSEWPC's National Waste Policy (2009), there are six key areas that would help to reduce landfill:

The six key areas are:

1. A shared responsibility for reducing the environmental, health and safety footprint of products and materials across the manufacture-supply-consumption chain and at end-of-life.
2. Improving the market through efficient and effective use of waste and recovered resources.

3. Pursuing sustainability through less waste and improved use of waste to achieve broader environmental, social and economic benefits.

4. The reduction of potentially hazardous content of wastes with consistent, safe and accountable waste recovery, handling and disposal.

5. Tailoring solutions to increased capacity in regional, remote and Indigenous communities to manage waste and recover and re-use resources.

6. Providing evidence, and access by decision makers to meaningful, accurate and current national waste and resource recovery data and information to measure progress and educate and inform the behaviour and the choices of the community. (DSEWPC, 2012)

In conclusion, although there has been an increase in the amount of waste material, being recycled, there is still a large amount that enters landfills. Over the last 10 years waste generation in Australia has increased by 31 per cent to 43.8 million tones over the period 2002-03 to 2006-07 (Australian Government's Department of Sustainability, Environment, Water, Population and Communities (DSEWPC, 2009). According the Australian Bureau of Statistics, between 2006-2007 construction and demolition waste contributed the most significant share, at 38 per cent, to landfill (ABS, 2010).

There is a growing social outcry in regards to the use of landfills (Jackson-Smith, Caplan & Grijalva, 2005) giving much doubt to the future of landfill projects. It is for these reasons that more waste materials should be included in the contemporary construction of small scale buildings and there is an important opportunity now to do more research on waste material reuse, either in the creation of new products or the invention of alternative building materials.

4.1 Objective 3: Which specific waste materials are suitable for inclusion in construction?

There are two potential sources of waste materials for use in construction: household waste and manufacturing waste. Some of these are already being used in construction which will be discussed at the end of this section

4.1.1 Household waste

There are approximately five types of materials that are commonly recycled from households. These include aluminium, papers & cardboard, glass, plastics, and steel.

Aluminium. The recycling of aluminium produces significant financial savings over the production of new aluminium even when the cost of collection, separation and recycling are taken into account (The International Aluminium Institute, 2001). The process of recycling aluminium involves the shredding and melting of the metal, which only exerts 5% of the energy it takes to form the metal from its virgin material bauxite.

Steel. Steel is a ferrous metal and therefore is 100% recyclable and can be recycled an infinite amount of times. This means that recycling steel saves energy and raw materials each time it is re-processed. Most steel has around 20% recycled content (BlueScope Steel, 2011). The process of recycling steel is very similar to aluminium as it is melted and reprocessed.

Paper & cardboard. The process of paper recycling involves mixing used paper with water and chemicals to break it down. It is then chopped up and heated, which breaks it down further into strands of cellulose, a type of organic plant material; the mixture is called pulp, or slurry. It is strained through screens, which remove any glue or plastic that may still be in the mixture then cleaned, "de-inked", bleached, and mixed with water. Then it can be made into new paper. The same fibers can be recycled about seven times, but they get shorter every time and eventually are strained out (The Technical Association of the Pulp and Paper Industry, 2001).

Glass. Glass is collected by a local municipality, then crushed and melted and molded into new products. Common recycled glass products are bottles, jars, bricks or decorative products. Glass does not degrade throughout the recycling process, which means that it can be recycled an infinite number of times (The Guides Network, 2012).

Plastic. Before recycling, most plastics are sorted according to their resin type. Some plastic products are also separated by colour before they are recycled. The plastic recyclables are then shredded and the fragments undergo a process to eliminate impurities such as paper labels. This material is melted and often extruded into a form of pellets which are then used to manufacture other products (Wansbrough & Yuen, 2002).

4.1.2 Manufacturing waste

Polyurethane. Polyurethane foam waste is one of the residues of manufacturing processes in the textile industry, the disposal of which is becoming a severe environmental problem. Hence, Rey, Alba, Arenas and Sanchis (2011), investigated the sound absorption properties of different materials developed from ground polyurethane foam waste and found that these recycled materials exhibit good sound absorbing properties. This suggests a potentially viable alternative to conventional materials for applications involving sound reduction.

Plastic. In a study of recycling/energy-recovery technologies for recycling plastic, Chen, Xi, Geng & Fujita, (2011), suggest that the promotion of new recycling programs for waste plastics could contribute to additional reductions in greenhouse gas emissions and fossil fuel consumption. Due to the amount of plastics produced in most countries, recycling plastics may become an important way to significantly reduce green house gas in the future.

In another study (Rajendran et. al, 2011) a life cycle assessment (LCA) approach demonstrated that recycled plastics can reduce environmental impacts by eliminating the need for mining and the transportation of natural gas and oil in plastic production. Rajendran et. al (2011) also found that adding reinforcement from waste glass fibres and flax fibres has the potential to increase the recycling rate and the number of functional applications for recycled plastics.

Finally, a study of agricultural plastic waste by Briassoulis et. al (2012), found that the majority of agricultural plastic waste retained their mechanical properties after use, thus preserving their quality during recycling. The study also found that the chlorine and heavy metal content of the agricultural plastic waste materials was much lower than the maximum acceptable limits for their potential use in cement industries. Agricultural plastic waste appears to be a viable material for use in construction which has been overlooked by current construction practices.

4.1.3 Waste materials currently used in construction

McElroy (2007) proposes that there is a large amount of recyclable materials that can be used in residential construction. He refers to a 406-acre neighbourhood development in the United States which is one of the greenest developments in the country. This is due to its single-family houses featuring rooftop solar panels, hook-ups for electric cars and floors made from recycled tyres.

The UK Government’s Sustainable Buildings Task Group recently recommended a benchmark of a minimum 10% of reused/reclaimed or recycled content (by material value) to be used in construction projects (Emery, et. al., 2007). In a study aimed at informing decision-making on the feasibility of setting and meeting such a requirement, Emery, et. al (2007) investigated current levels of recycled content in Defence Estates’ standard design for modern barracks accommodation. The existing designs for new barracks were found to use nearly 20% recycled and recovered materials. The project identified opportunities to increase this proportion to nearly 25% with no increase in cost or risk. Some examples of waste materials used in construction include foundry sands, concrete aggregates and tyres and bottles.

Foundry sands. The use of recycled materials in construction is not new. Ten years ago, Finnish researchers where proposing the use of recycled foundry sands in earth construction (Mroueh & Wahlström, 2002). As a result of this research, a national production control standard was prepared to enable the reclamation of foundry sands, and also reclaimed concrete and blast-furnace slag as alternative aggregates.

Concrete aggregates. Initially, concrete aggregates were used to save on Portland cement and usually consisted of coarse and fine materials like crushed rock and sand. Maier & Durham, (2011), contend that the use of recycled materials in concrete mixtures creates less landfill and decreases the depletion of finite raw materials. They found that recycled material in concrete increased the strength and durability by up to 50% when compared with a normal concrete made from finite materials such as Portland cement and various aggregates. It is possible that anything that can be used in the binding process of concrete without reducing its strength could be used as an aggregate.

Tyres and bottles. Michael Reynolds’ Earthship construction (Sevier, 2009) has been using waste materials in construction for almost 20 years. He proposes a model of construction where tyres heavily packed with earth and stacked like bricks make up the structural walls of dwellings. Glass and plastic bottles are also used extensively in non structural walls to make up the main components of the dwelling (Sevier, 2009). However, it must be noted that Reynolds’ use of tyres, glass, and plastic bottles is not actually a form of recycling. Rather, it is a method of down-cycling where the materials can never be re-used in the future.

In summary, nearly all waste materials have some potential use in construction. Household wastes such as aluminium, glass and plastics can be recycled easily. It is currently difficult to determine the amount or the significance of these materials on the building industry as there are very few studies that discuss this. Household waste has the potential to provide new opportunities in material experimentation, particularly in terms of down-cycling. In the case of Michael Reynolds' Earthship construction, waste materials are reused immediately in non-structural walls without further processing. In terms of manufacturing waste there is significant potential for use, as these materials are usually available in large quantities. If these by-products could be reused it could create extensive environmental positives. Additionally, waste materials such as foundry sands being used as concrete aggregates has reduced their use in landfill and reduced the use of raw finite materials. These examples suggest there is a future for the increased use of waste materials for dwelling construction.

4.2 Objective 4: what are the barriers that prevent greater use of waste materials in contemporary dwelling construction

The main barriers to greater use of waste materials are waste disposal procedures and costs, limited research, and inflexible building codes.

Waste disposal costs. There are situations where the cost involved in recycling materials outweighs the benefits. Metals in particular are often inefficient to recycle. In a study of the recycling of 60 different metals, Graedel et. al (2011) found that there are relatively low efficiencies in the collection and processing of most discarded products, various limitations in recycling processes, and the fact that primary material is often relatively abundant and low-cost these factors mean that many end-of-life recycling rates are very low. At present, only 18 metals (silver, aluminium, gold, cobalt, chromium, copper, iron, manganese, niobium, nickel, lead, palladium, platinum, rhenium, rhodium, tin, titanium, and zinc) have end-of-life recycling rates of above 50% (Graedel et. al, 2011). The dependence of recycling on economics, technology, and other factors, influences which materials are recycled & readily available for use in construction.

Moreover, systems of waste management have been refined over a long period of time to handle the increasing volume & waste. They are firmly entrenched, rigid and inflexible. Attempting to introduce new ways of using waste material will prove difficult as these systems appear to be working well from a cost efficiency perspective but without much priority given to the environmental impacts are well known. Additionally, there is likely to be strong resistance to new ways of using waste from those involved in waste management if there are no financial gains to be made.

Limited research. It is apparent from the literature that there has not yet been enough research in this area. The current research focuses mainly on concrete and its possible aggregates. There is an absence of innovative thinking regarding other materials that can be applied in construction. A larger bank of research in this area would encourage more waste materials to be used thus reducing landfill and easing the pressure on current waste management systems which can be expensive and not helpful to the environment in the long term.

Inflexible building codes. Building legislation and building standards will need to become more flexible to allow more alternatives to traditional construction materials to be used. At present there is no specific allowance or guidance for the implementation of waste materials in construction. However, the Building Code if Australia (BCA) will not be amended unless there is clear evidence that these materials are safe and viable alternatives. This can take a long time as changes to the code will only occur in the following situations:

- There is a rigorously tested rationale for the regulation;
- The regulation generates benefits to society greater than the costs (that is, net benefits);
- The competitive effects of the regulation have been considered and the regulation is no more restrictive than necessary in the public interest; and
- There is no regulatory or non-regulatory alternative that would generate higher net benefits. (Australian Building Codes Board, 2011)

Such delays in allowing new materials to be approved has been a barrier in the USA where alternative dwelling construction methods such as Michael Reynolds' Earthships have met with strong government opposition (Hodge, 2007).

In summary, the main barriers to the implementation of waste materials in contemporary dwelling construction are waste disposal costs and the current well established methods of C&D waste disposal, legislation such as the Building Code of Australia & The Australian Standards, and limited research on the variety of alternative construction materials available or in development. The next section of this paper examines three case studies where waste materials have been used and where there is potential to increase waste material use in dwelling construction (Research Objective 5)

5 Case Studies

There are two aspects that have influenced the selection of case studies in this paper. Firstly, they must demonstrate that waste materials have been used in the building and secondly, they must have the potential to increase the use of waste materials in the construction industry by being realistically and easily incorporated into contemporary small scale construction (e.g. dwellings).

Each case study commences with a description of the way in which specific waste materials are used in construction of the dwelling. The second step identifies where more waste materials could have been used. Areas where improvements may be identified include:

- The basic design
- Structural elements
- Aesthetic properties
- Material selection
- Functional requirements.

Finally, barriers to the implementation of waste materials in construction are discussed at the end of each case study.

6 Case Study 1:

6.1 Introduction

This case study investigates the use of waste materials in a prototype student housing pod project by Auburn University Rural Studio, located in the United States. This project focused on using corrugated board in construction of the dwelling (Mockbee et. al, 2010). This material is a waste product from households and manufacturing.

Corrugated board is commonly used as a permeable rigid container to package pizzas, appliances and light bulbs during shipment and is often mistaken for cardboard. While cardboard is a single, thick layer of paper fibres, corrugated board consists of three layers of paper glued together. The outer layers are flat while the inner layer is corrugated. This creates a very strong, lightweight panel (Twede & Selke, 2005). After the corrugated sheets are produced, a die-cutter cuts the final box shapes out of the board and the remaining clippings are waste which are sent to become bales.

Sometimes the corrugated sheets are treated with wax to create a more water-resistant container (Mockbee, et. al, 2010). According to Michler (2010) when corrugated board has been treated with wax, it is almost impossible to recycle, therefore, a lot of this waste is sent to land fills. The manufacturing process of corrugated board produces, at one plant alone, 50 waxed bales at 453kgs each are produced each day. This creates approximately 22679 kgs of industrial waste that is traditionally considered as unusable and sent to a landfill (Mockbee, et. al, 2010). Finding an alternative use for waxed corrugated board as a construction material can significantly reduce land fill.

6.2 Current use of waste materials

This project down-cycles corrugated board and compresses them into bales. The compressed corrugated board bales form the structural walls, foundations and a flooring system. Large reclaimed timber members tie the structure together while also providing scope to attach the roof form. Corrugated bales were also used as a flooring system by encasing them in a thin layer of cement and earth (Mockbee, et. al, 2010).

Additionally, this project experimented with rendering the bales in aluminium paint, Portland cement (adobe), corrugated clippings and earth, suggesting that work is still continuing on ways of using compressed corrugated bales for construction.

6.3 Opportunities for increasing waste usage

This project has the potential to use more waste material as outlined in the next sections.

6.3.1 Basic design

Generally speaking, the overall size of the pod limits its potential use of waste material. This is understandable as the pod concept is still in its experiment/developmental stage. However, waste material usage could be increased by changing the design from the existing individual rectangular pod to a more complex form, and adding multiple pods and circulation spaces. The addition of a second story, though structurally challenging, would considerably increase if not double the use of this waste material.

6.3.2 Structure

Structurally, this project already uses a recently proven structural system of compressed corrugated board bales. However, there is potential to replace structural members with an alternative material (see material selection)

6.3.3 Material selection

In terms of material selection, there are other waste materials that could be a viable alternative to the timber members used in the pods. An Australian company, Cosset, manufactures a product that combines 100% recycled plastic with any organic matter from saw dust to rice husks. This material is claimed to be stronger than pure recycled plastic. Additionally, the product dubbed EVERTUFF (Cosset, 2012) is impermeable, termite and rot proof and has a life span that exceeds 40 years (Cosset, 2012).

6.3.4 Functional requirements

This building functions as a type of studio apartment. This means that it needs to meet the natural lighting, thermal and airflow comfort zones associated with personal dwellings. This experimental structure meets all these requirements through its large windows, and high level of thermal mass.

6.3.5 Aesthetics

From a subjective point of view, the bales would be more aesthetically appealing if they were rendered in a similar way to rendered straw baled dwellings. The dwelling could therefore also be more closely identified with rendered conventional dwellings which are a popular choice in the building industry. Render is a combination of sand, Portland cement, admixtures and water which results in a mixture that once dry, is versatile, strong and durable against exterior exposure and moisture (Ravindrarajah & Mansour, 2009). In traditional rendering, the Portland cement and the admixtures act as the binding agent, so it can be assumed that the sand is substitutable through down-cycling alternative materials with a same or similar consistency. Some suggestions for waste materials that can be used as alternative binding agents are waste tyre rubber powder, ground plastic, saw dust. Additionally the use of rendering or bagging would increase the life span and durability of the material by encasing it to keep out moisture and foreign particles, thus providing aesthetic and environmental advantages.

6.3.6 Potential barriers to the use of waste materials

The replacement of sand in traditional render by rubber powder, ground plastic or saw dust are speculative concepts only as there is a lack of research into the material science behind render aggregate substitution. In terms of cost, it is uncertain the difference between rubber powder and sand. Assuming that the sand is processed in some way, i.e. manufactured or riverbed sand, we might find that rubber powder is easy to produce as its process is very simple.

The public acceptance of the compressed corrugated fibre board, and the alternative render aggregates could provide a barrier if it is not aesthetically pleasing. However, the appearance of rendered straw bale houses are already acceptable to home owners using them and the alternative render aggregates should technically not change the look of render. Therefore, clients choosing to render their home are unlikely to have any objections to the material being used.

7 Case Study 2:

7.1 Introduction

Westwyck is a sustainable residential development that has refurbished the Brunswick West Primary school. This refurbished school aimed to bring the building back to life as an urban showpiece of sustainable development and quality design. With the use of inert materials such as hoop pine and non-toxic paints and finishes, and low formaldehyde materials, Westwyck boasts that it is a sustainable development that offers a clean and healthy living environment (Westwyck, 2008).

The development consists of a communal, shared housing cluster, five new town houses on the school grounds and seven warehouse-style apartments carefully designed into the classrooms and corridors of the Victorian era school building (Westwyck, 2008).

The key sustainability principles that Westwyck use to call itself an 'ecovillage' are materials efficiency, energy efficiency and water efficiency. The cutting edge water management system is pushing new boundaries in reducing reliance on mains water and minimising the discharge of waste water to sewer or storm water drains.

7.2 Current use of waste materials

Westwyck re-uses construction and demolition waste for all of its construction materials, thus reducing landfill. These materials make up the structural systems, the flooring, the enveloping system and many other aspects of the built environment. Additionally, as this development re-occupies the existing school building, there is a large amount of material that has been moved or reused from demolition of out buildings and the internal walls in the existing school building.

7.3 Opportunities for increasing waste usage

In this type of development, the materials used are only down-cycled C&D waste but there is more scope for these materials to be complemented by waste materials that could be retrofitted into the building (See Material Selection section).

7.3.1 Basic design

There is scope to divide the larger spaces within the school building with non-structural internal walls by down-cycled waste materials. An initial suggestion would be to adapt the methods of Earthship construction (Sevier, 2009) into non-structural walls. This would mean using discarded plastic bottles, glass bottles and/or aluminium cans, Portland cement, a recycled aggregate of some sort and water. This is achieved by using a brick like method of stacking the bottles, as discussed in the literature review.

7.3.2 Structure

There is little scope for increasing the use of waste materials in a structural sense as this project utilises an existing building where a lot of the structural components were already in place before the development started.

7.3.3 Material selection

The conventional construction method of a mixture of precast or in situ or tilt up concrete panels and stud framing used in this project could be replaced by a waste based alternative. A product manufactured by a UK company called Thermo Poly Rock (TPR3™), claims to be stronger and cheaper than concrete. Its manufacturing process provides a similar product to precast concrete however, but it is made from 100% recycled waste plastics (Affresol, 2010). This material can easily be substituted for the concrete in this scenario.

The conventional timber framing construction of the dwellings lends itself to the use of insulation. A company closely tied with the University of Cambridge, has found that just 12.5mm of rice husk ash can achieve the equivalent of over 100mm of conventional petroleum-based insulation (Visser, 2009). This means that this product, Vacuum Insulated Panels™ (VIP), could become a greener more viable alternative to traditional insulation than has been used in the Westwyck project.

The internal aspects of Westwyck dwellings are mostly down-cycled or reclaimed materials. Cabinets are constructed from salvaged wainscoting, the chimneys are reconstructed from lining boards and in the bathrooms of the dwellings, the old science room basins have been reused (Westwyck, 2008).

7.3.4 Functional requirements

There is scope to retrofit the buildings with waste materials that will enhance their functional performance. For example, insulation can be improved with the addition of BioPCM™ panels which improves the thermal mass of the dwellings and decreases energy use. Additionally, this will also regulate the interior temperature decreasing the need for mechanical heating and cooling. It should be noted that BioPCM^{TM} panels are made from organic waste materials such as coconut oil, vegetable oil and fats. This takes advantage of the natural tendency of material to absorb heat when they melt and to release heat when they solidify. These materials are referred to as phase change materials (PCM). When these phase change materials are placed in quantity into the structure of a building, they absorb heat during the day and realise heat at night (Phase Change Energy Solutions, 2012).

7.3.5 Aesthetics

There is reclaimed C&D waste used in the façades of the residential dwellings in the Westwyck development. This includes a composition of rendered concrete panelling around the ground floor, a weather board look on the second floor and reclaimed timber elements on the façade. Additionally, some of the aesthetic appeal comes from the re-creation of a school like aesthetic that has been carried over from the existing building using these reclaimed materials.

7.3.6 Potential barriers to the use of waste materials

The concept of changing the basic design of the Westwyck development to adapt Earthship construction to the non-structural dividing walls contains a myriad of legislative and building code problems that need to be successfully negotiated before any work of this type can be undertaken. This is one of the reasons why Earthship construction methodologies have not been adopted by mainstream construction industry in the USA (Hodge, 2007).

It's also possible that these alternative materials might cost more to manufacture. This is potentially the case with BioPCM^{TM} panels where the benefits may be outweighed by its purchase cost. Unless its energy saving capability can be measured in dollar terms, it's likely that its acceptance in the construction industry and by the public will be slow.

8 Case Study 3:

8.1 Introduction

This case study examines the use of recycled and renewable materials of 60Leicester Street, and how these materials can be complemented or replaced with waste materials. 60L is a 3 storey warehouse with a rooftop garden and is one of the premier sustainable developments in Melbourne. 60L is the headquarters of the Australian Conservation Foundation and leases its office space to other tenants. What is notable here is that the ACF hold these tenants to a green lease (Australian Conservation Foundation, 2012).

60L uses a large amount of recycled and renewable materials such as plastics, plantation pine, aluminium, cardboard and cork. It reuses the original warehouse building and has down-cycled most of the interior elements. These down-cycled elements make up the structural system, stairs and flooring.

As this is a small scale commercial building the processes and use of waste materials can cross over to residential dwellings and vice versa. This final case study was chosen because it is an excellent example or benchmark of what is possible in waste materials use in construction. In the case of 60L the heading for suggested improvements used for the previous case studies will be used as examples.

8.2 Current use of waste materials

60L implements a large amount of recycled and waste materials but one of the most notable is shredded plastic bags that are reformed into carpet (Green Living Tips, 2012). These are laid in an individual square format, which eliminates waste by allowing each square to be replaced when it is damaged or worn out. Also of interest are the static room dividers which are made from a mixture of a fibreglass by-product, polyethylene-terephthalate (PET), and potato starch (Charles Sturt University, 2011). This creates a permeable linen like material. 60L's roof top garden is made predominantly with recycled aggregate and consists of planter boxes and a barbeque space. Additionally, the bricks that were removed from the original warehouse building are repurposed to form structural internal walls.

8.3 Opportunities for increasing waste usage

The PET and potato starch static room dividers in 60L, could also be used near windows within the building where they could function as internal sun shades, curtains, and used as internal walls depending on acoustic functional requirements of the building's tenants. This product has the potential for further research in terms of fire retardation, isolative qualities and acoustic resonance. In addition, the rooftop gardens use of concrete and recycled aggregate could implement more waste materials by integrating fly ash or foundry sands as fine aggregate within the concrete mix.

8.3.1 Basic design

In terms of the basic design the reuse of the original warehouse and its structural member does not leave much to scope for expansion. However, there could be an issue in the design if the structural members are below specification for the function of the floor, which would result in the existing structure being buttressed, however the cost would still be minimal.

8.3.2 Structure

As the structure consists of reclaimed timber members from the original warehouse there is little scope for waste materials to be applied to this building aspect.

8.3.3 Material selection

In terms of material selection, 60L's use of recycled, reused, renewable materials is quite extensive. However, there is scope here for BioPCM™ which was mentioned earlier its ability to work in conjunction with insulation means that it can be implemented very easily.

As much as this building boasts sustainability and the use of renewable resources, its windows and frames are made from raw materials. This can be easily substituted for recycled aluminium window frames and recycled glass windows.

8.3.4 Functional requirements

As the main function of 60L is an office space there needs to be consideration of abundant natural light, air flow and fluidity of movement. The PET and potato starch dividers could be used as egress markers to provide division in the space and allow natural light and air to flow through.

8.3.5 Aesthetics

The aesthetics of the interior of 60L is very well designed and its atrium predominantly uses reclaim materials, therefore the scope for increasing waste materials is quite small.

8.3.6 Potential barriers to use of waste materials

The only potential barrier in this scenario is that the use of reclaimed materials in 60L limits the ability to add waste materials that would improve the content of sustainable materials already present in the building.

9 Discussion

It has been difficult to find many examples of waste materials used in dwelling construction both in the literature and during the process of selecting the case studies. There clearly interest by the public and in the industry in moving away from the use of non-renewable resources in construction and towards better use of waste and recycling materials for renovations and construction. This is seen in the public arena with websites to help people source recycled materials (Alterman, 2005) and in the construction industry with websites such as Ecospecifier.com (2012). There have been attempts by governments to recycle and reduce waste (DSEWPC, 2012) and by manufacturing industries to use new technologies to reduce waste at its manufacturing source (Zhang, Wu & Shen, 2012). However, there is still an increasing amount of waste that is difficult to manage other than placing it in landfills.

There is great potential for the construction industry to reduce its own waste and to absorb waste from other areas such as household waste and manufacturing waste by incorporating it into dwelling construction. The three case studies have examined various opportunities for greater use of waste materials in buildings that already use recycled, reclaimed, and/or waste materials such as compressed corrugated fibre board walls (Case Study 1), reclaimed materials and re-use (Case Study 2) and integration of synthetics and natural products (Case Study 3)

Suggested improvements to these projects and observations included:

- Replacing timber members with recycled plastic members such as EVERTUFF™ (Case Study 1)
- Replacing concrete panels with Thermo Poly Rock™ (Case Study 2)
- Rendering for aesthetics by using alternatives to fine aggregates (Case Study 1)

- Enhancing thermal mass using organic waste products such as oils and fats via Bio PCM panels (Case Study 2)

- Replacing petroleum based insulation with Vacuum Insulated Panels^{TM} made from rice husk ash (Case Study 2).

- Products that can integrate synthetic materials and natural materials to create a aesthetically pleasing building element i.e. PET and potato starch static dividers (Case Study 3)

- Structural reuse of existing building elements which significantly lowers cost even if additional structural support is needed. (Case Study 3)

The most important of these suggestions is replacing concrete panels with other materials as concrete has a high embodied energy value (Haynes, 2010) and is a finite material. This would also explain why there has been a focus on reducing concrete with a variety of other aggregate materials, some of which are waste materials (Maier & Durham, 2011). Any suggestions that use plastic waste (eg, EVERTUFF^{TM} and Thermo Poly Rock^{TM}) are also welcome as plastic waste represents one of the most and imperishable materials when left in landfill.

The literature review and case studies also suggest that there is an unsystematic approach to waste materials which seems to be driven by the latest technologies and by innovative companies trying to bring their products to the construction industry market. How well these innovations are accepted by the industry is dependent on the demand for the product by builders and the public (home builder). Demand in both cases is likely to be driven by the costs involved in using the waste alternative compared to conventional materials. Equally important are the building regulations such as the BCA which restricts the selection of materials to only those that have been approved by the BCA.

Although the BCA creates an obstacle for experimental waste materials, it closely guards the integrity of the building industry. Its major goal is to enable the achievement of a uniform national policy, minimum necessary standards of relevant, health, safety, amenity and sustainability objectives efficiently (Australian Building Codes Board, 2011). While this is a good thing, there are lickley to be long delays in bringing new materials and innovations into being because of complex processes in changing aspects of the code.

10 Conclusions and recommendations

This research has investigated some of the alternative waste-based materials that could ultimately replace more conventional and less sustainable building materials used in dwelling construction. The current building industry does not appear to have any standard or systematic procedures in place for the use of waste material, be it reclaimed or experimental products made from by-products. The literature and the case studies in this paper demonstrate that there is an intention and desire amongst some in the industry to adopt waste materials in construction and that new technologies are offering more alternatives as time goes on which is a positive step forward.

Another conclusion gained from the case studies is that it is possible to retrofit existing structures with waste materials, such as the BioPCM^{TM} thermal panel, TRP and VIPs and this would increase the use of waste materials in existing dwellings decreasing the amount of waste material in land fills and ultimately creating a more environmentally conscious waste management system.

The Australian Government and the construction industry can help to increase the use of waste material In dwelling construction by:

- Encouraging retrofitting of building with more waste materials where possible (eg; BioPCM^{TM} insulation

- Providing testing sites for experimental buildings

- Streamline the BCA approval processes for new materials that could be used in dwelling construction

- Provide financial assistance or subsidies to help offset the cost of new waste materials when they are introduced to the public and industry. This will h elp them to be accepted more easily and quickly

- Provide money to fund research into new technologies and the barriers that prevent or slow their acceptance in mainstream use.

For architects, designers and builders, there is also the problem of inflexible thinking in terms of using waste materials as these professions traditionally focus on using as little material as possible. In the case of materials made from waste, there is a need for a paradigm shift to thinking about how much of these materials could be used in dwelling construction. Zhang, Wu, & Shen (2012) already make some recommendations as to how this can be achieved.

In terms of waste produced by the construction industry itself, there are encouraging signs that C&D waste is already top of mind in some construction industries. The EU target to reduce C & D waste by 45% before 2020 (Llatas, 2011) is a good example of this. However, there is still a lot of waste being produced that is of great environment concern overall.

There is potential for the construction industry to not only take care of its own waste but to play a major role in reducing landfill by using the waste created by other industries. The literature review and case studies discussed in this paper have highlighted some of the innovative ideas and technologies that have already begun to address these environmental problems. These are encouraging signs that the world is becoming more self conscious in terms of sustainability and that the building industry starting to take some responsibility to finding solutions to the pandemic of a wasteful society.

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