DURABILITY STUDY OF EPOXY-BASALT FIBER COMPOSITE REBAR FOR CONCRETE REINFORCEMENT

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Virtual Presentation
NJ SAMPE CHAPTER
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MENU
Chef's Delight
Concrete, Infrastructure, FRP bars and its use today
Starters
Durability methods, FRP bar durability today, and service life
Main Course
Basalt FRP rebar, materials, tests, aging, SEM and results
Dessert
Conclusions and knowledge gaps


WINE LIST
CURATED BY
TEETERING IN THE UNKNOWN
BUBBLES
Opportunity, 2021
RED
Opportunity, 2021

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INTERMISSION

The average worldwide usage of concrete is estimated as more than **ONE TON PER YEAR** for every human on earth

…that about 10 billion ton annual production.

That is approximately **TWICE** as much as steel, wood, plastics and aluminum **COMBINED…**

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…concrete usage is **only exceeded** by the usage of **FRESHWATER**.

This makes concrete the **MOST USED MAN-MADE** product on the planet.

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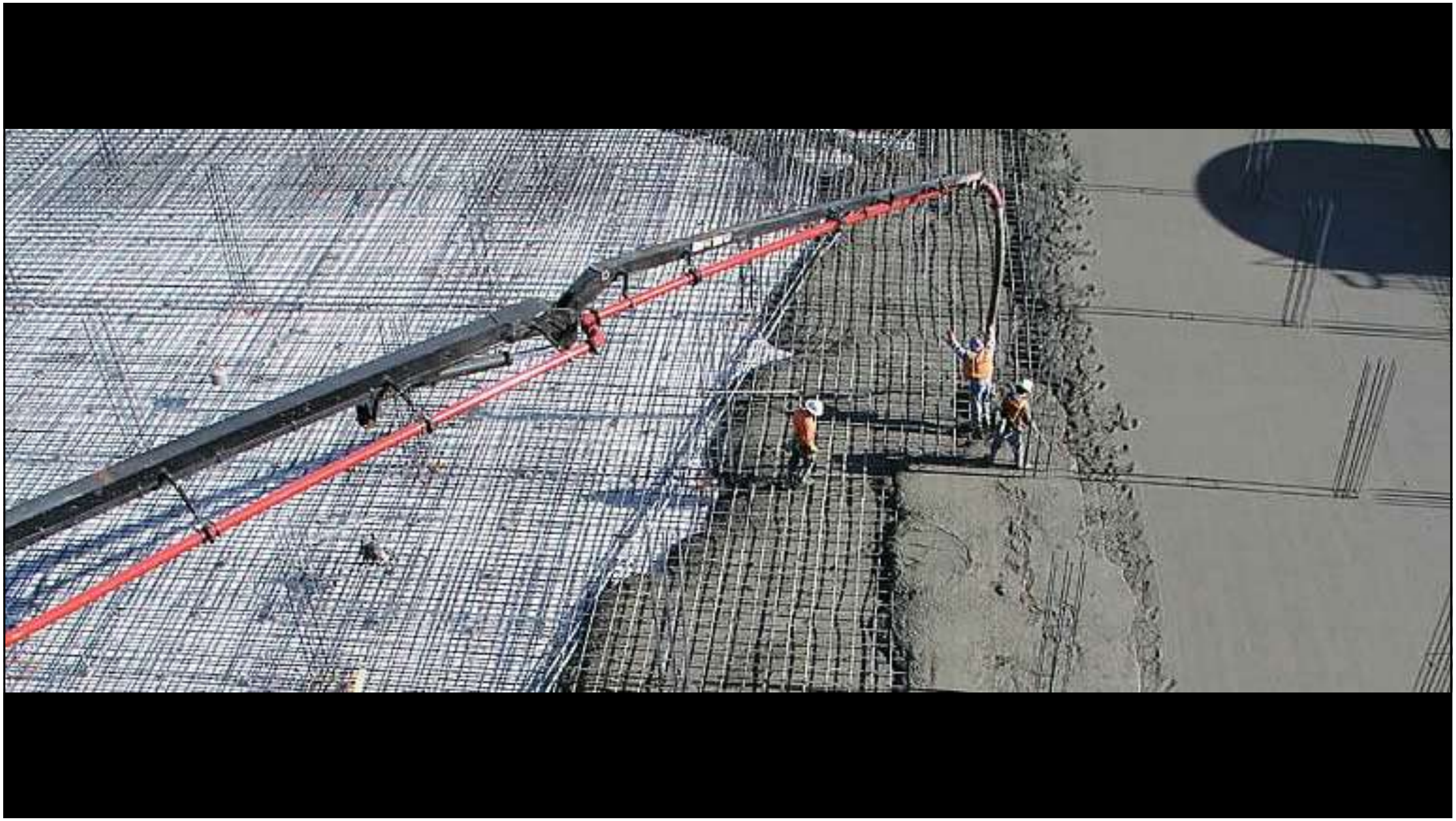

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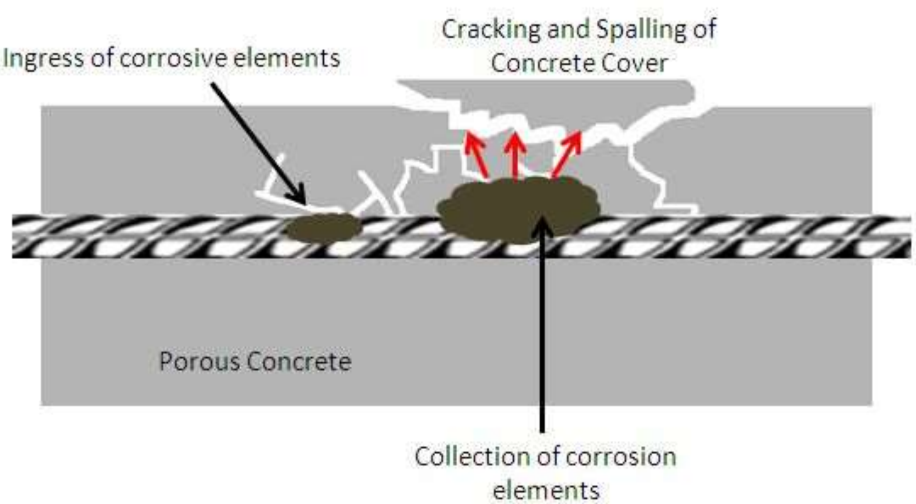
Corrosion caused by the ingress of **chlorides** from saltwater, aggregates and cement.



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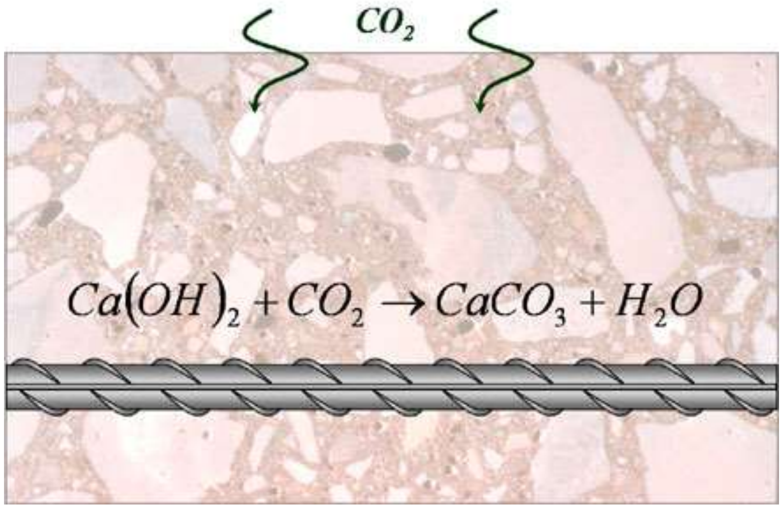
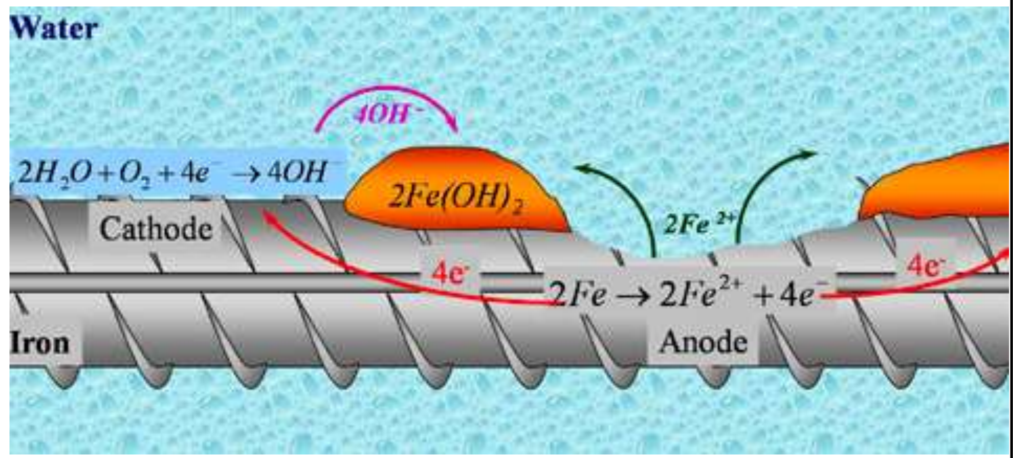
Corrosion **in steel,** reinforcing the concrete





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SERVICE LIFE OF STRUCTURES GREATLY REDUCED BY CORROSION

- Failure mechanism for concrete structures exposed to aggressive environments is often corrosion of steel reinforcement
- Traditional corrosion mitigation efforts:
  - Admixtures
  - Increase Concrete Cover
  - Alter Concrete Mix
  - Membranes & Overlays
  - Epoxy-Coated, Galvanized or Stainless Steel

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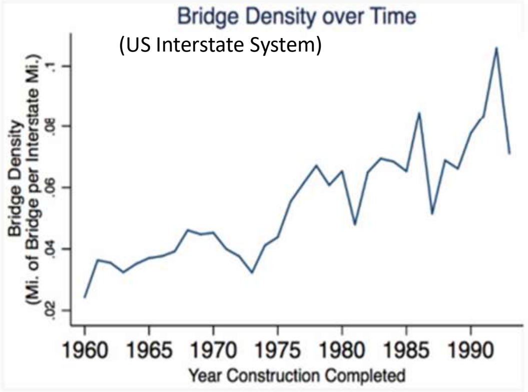
WHY? INFRASTRUCTURE FACTS…



Infrastructure owners are seeking:

- Increased service-life;
- Reduced maintenance & service liability;
- Resilience;
- and sustainability (sometimes!)

Traditional construction materials cannot reliability meet all these challenges without periodic intervention (corrosion mitigation & re- re-strengthening):

- USA: total annual cost of corrosion reported as **$276 billion** in 2002
- Bridge decks maintenance due to corrosion about **$2 billion**;
- Substructure another **$2 billion** (FHWA, 2002) – mostly from seawater

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** CAS. 2014. "Corrosion Status of China and the Control Strategy Research," Chinese Academy of Sciences, Beijing, China, www.cas.cn*

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INSTEAD OF MITIGATION…
WHY NOT ELIMINATE THE PROBLEM?

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FRP REBARS KEY BENEFITS…

…Low to almost no maintenance
…four times lighter than steel
…higher tensile strength

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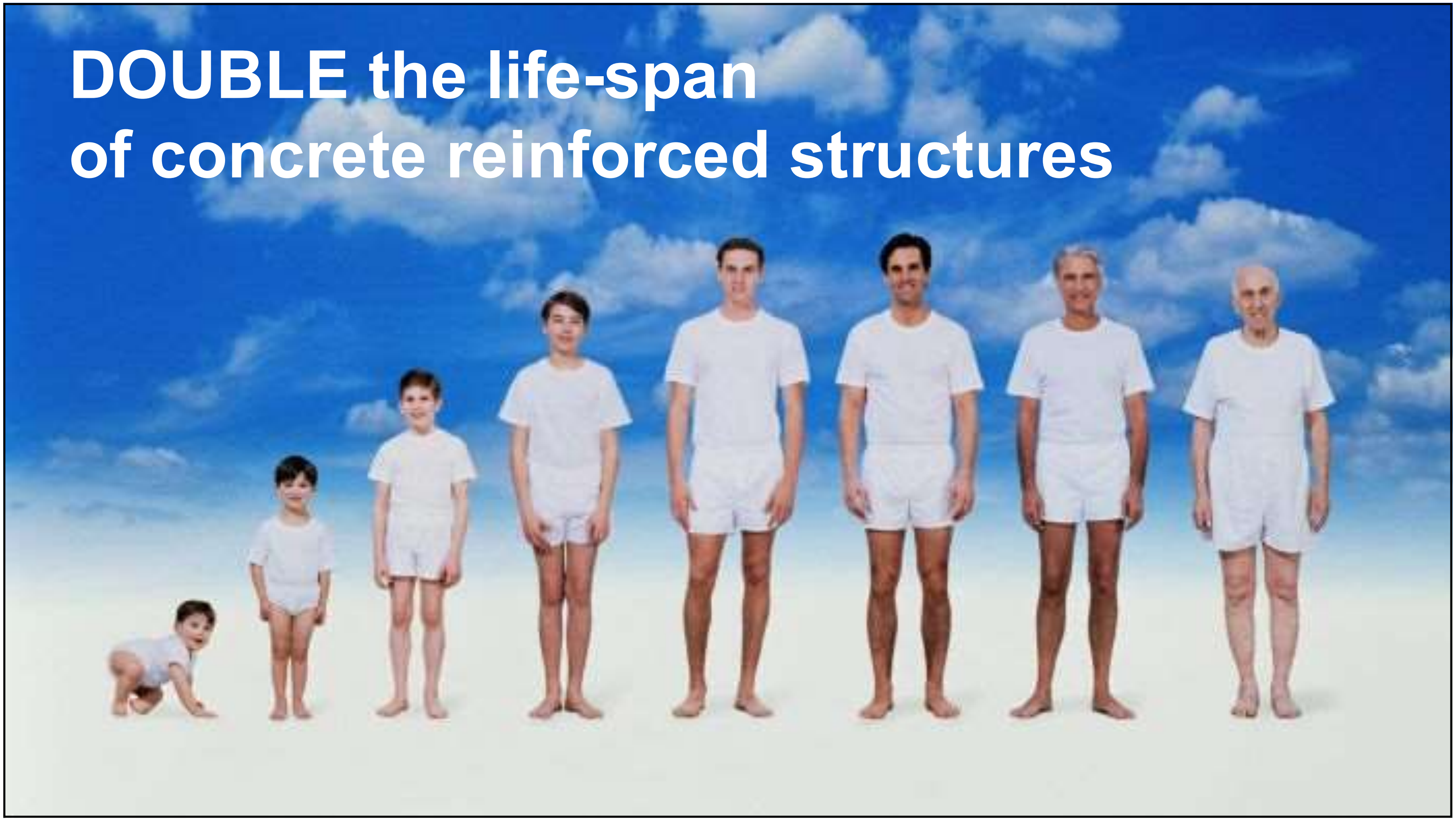
DOUBLE the life-span
of concrete reinforced structures

FRP DURABILTY…

Two main methods used to assess and validate the durability of FRP bars:

1. Accelerated aging protocols (high temperature) → fast
2. Extraction of samples from real life structures → real

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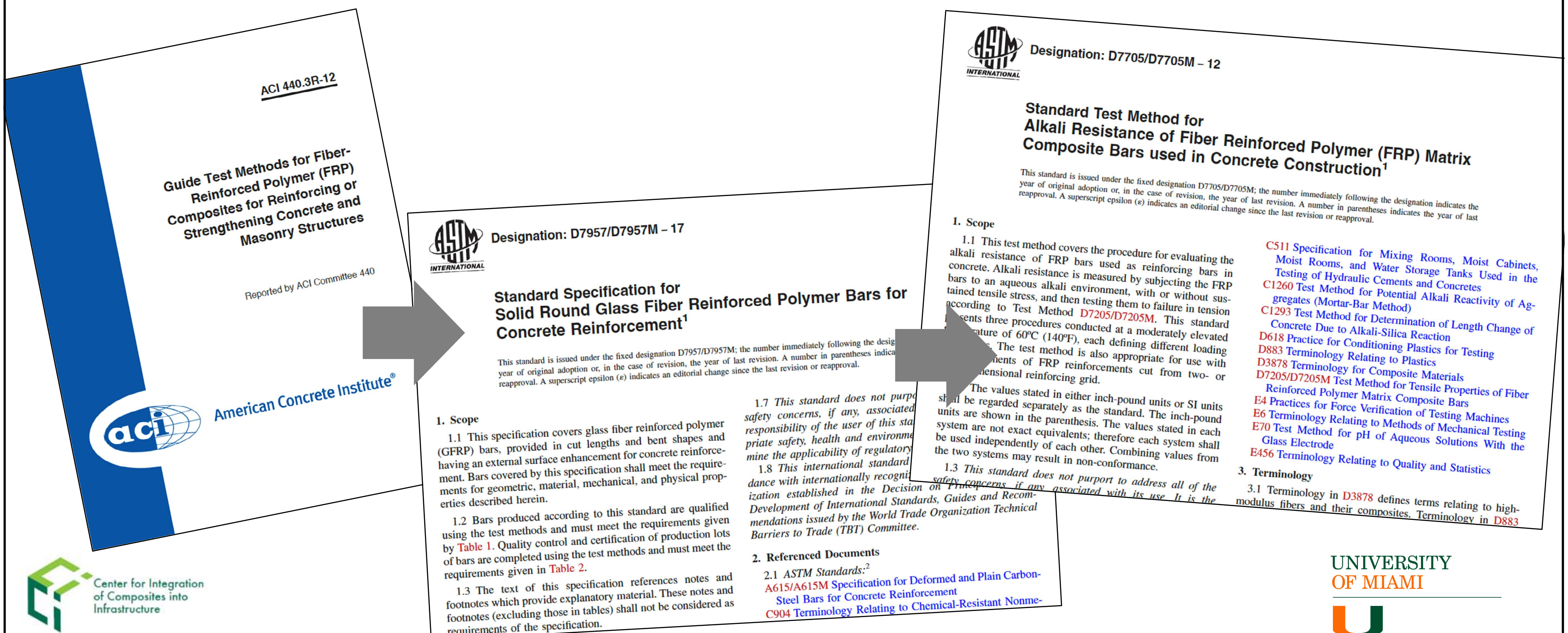
FRP DURABILTY…

Long established accelerated conditioning protocol:



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ACCELERATED, WHAT DOES IT ACTUALLY MEAN?

Designation: D7705/D7705M – 12

INTERNATIONAL

Standard Test Method for Alkali Resistance of Fiber Reinforced Polymer (FRP) Matrix Composite Bars used in Concrete Construction[1]

This standard is issued under the fixed designation D7705/D7705M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the procedure for evaluating the alkali resistance of FRP bars used as reinforcing bars in concrete. Alkali resistance is measured by subjecting the FRP bars to an aqueous alkali environment, with or without sustained tensile stress, and then testing them to failure in tension according to Test Method D7205/D7205M. This standard presents three procedures conducted at a moderately elevated temperature of 60ºC (140ºF), each defining different loading conditions. The test method is also appropriate for use with linear segments of FRP reinforcements cut from two- or three-dimensional reinforcing grid.

1.2 The values stated in either inch-pound units or SI units shall be regarded separately as the standard. The inch-pound units are shown in the parenthesis. The values stated in each system are not exact equivalents; therefore each system shall be used independently of each other. Combining values from the two systems may result in non-conformance.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the*

C511 Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes
C1260 Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
C1293 Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction
D618 Practice for Conditioning Plastics for Testing
D883 Terminology Relating to Plastics
D3878 Terminology for Composite Materials
D7205/D7205M Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars
E4 Practices for Force Verification of Testing Machines
E6 Terminology Relating to Methods of Mechanical Testing
E70 Test Method for pH of Aqueous Solutions With the Glass Electrode
E456 Terminology Relating to Quality and Statistics

3. Terminology

3.1 Terminology in D3878 defines terms relating to high-modulus fibers and their composites. Terminology in D883

8.7 The alkaline solution in Procedures A and B shall be a composition representative of the porewater inside Portland cement concrete. The suggested composition of alkaline solution consists of 118.5 g of $Ca(OH)_2$, 0.9 g of NaOH, and 4.2 g of KOH in 1 liter (33.8 fl. oz.) of tap water. The solution shall have an initial pH value of 12.6 to 13.0 as measured by Test Method E70. The alkaline solution shall be covered before and during the test to prevent interaction with atmospheric CO_2 and to prevent evaporation.

TABLE 1 Property Limits and Test Methods for Qualification[A]

Property	Limit	Test Method
Mean Glass Transition Temperature	Midpoint temperature ≥100 °C [212 °F]	ASTM E1356
Mean Degree of Cure	≥95 %	ASTM E2160
Mean Measured Cross-Sectional Area	Table 3	ASTM D7205/D7205M, subsection 11.2.5.1
Guaranteed[B] Ultimate Tensile Force	Table 3	ASTM D7205/D7205M
Mean Tensile Modulus of Elasticity	≥44,800 MPa [6 500 000 psi]	ASTM D7205/D7205M
Mean Ultimate Tensile Strain	≥1.1 %	ASTM D7205/D7205M
Guaranteed[B] Transverse Shear Strength	≥131 MPa [19 000 psi]	ASTM D7617/D7617M
Guaranteed[B] Bond Strength	≥7.6 MPa [1100 psi]	ASTM D7913/D7913M
Mean Moisture Absorption to Saturation	≤1.0 % to saturation at 50 °C [122 °F]	ASTM D570, subsection 7.4
Mean Alkaline Resistance	≥80 % of initial mean ultimate tensile force following 90 days at 60 °C [140 °F]	ASTM D7705/D7705M, Procedure A
Guaranteed[B] Ultimate Tensile Force of Bent Portion of Bar	≥60 % of the values in Table 3	ASTM D7914/D7914M

Mean Alkaline Resistance

≥80 % of initial mean ultimate tensile force following 90 days at 60 °C [140 °F]

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HOW DOES 'ACCELERATED' ACTUALLY COMPARE?

- Completed research Investigation to draw conclusions on the long-term **durability of GFRP bars** after at least 15 years in service
- Cores extracted from **Eleven bridges** located across the United States

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HOW DOES 'ACCELERATED' ACTUALLY COMPARE?

Results indicated reduction in tensile strength of 2.13% over a period of 17 years of service…

… that would correspond to drop in strength of 12.5% over a period of 100 years (if the degradation rate is assumed to be linear)

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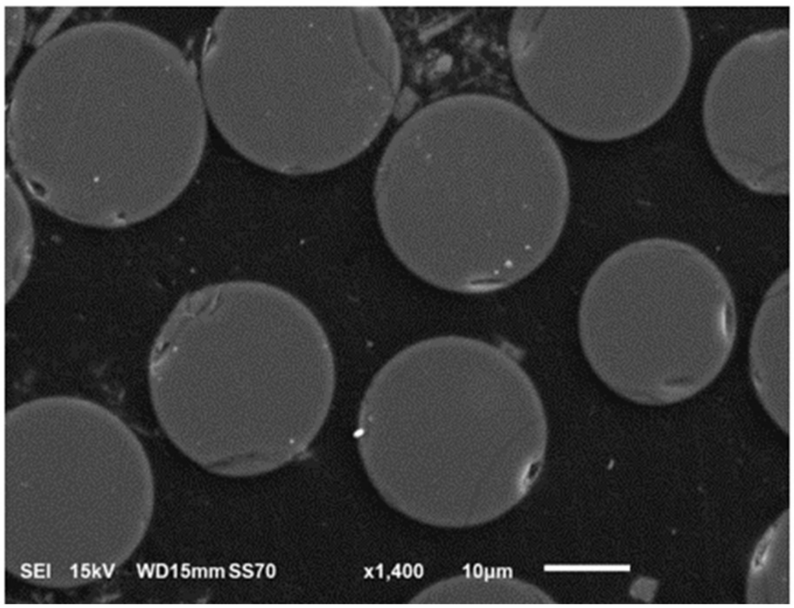
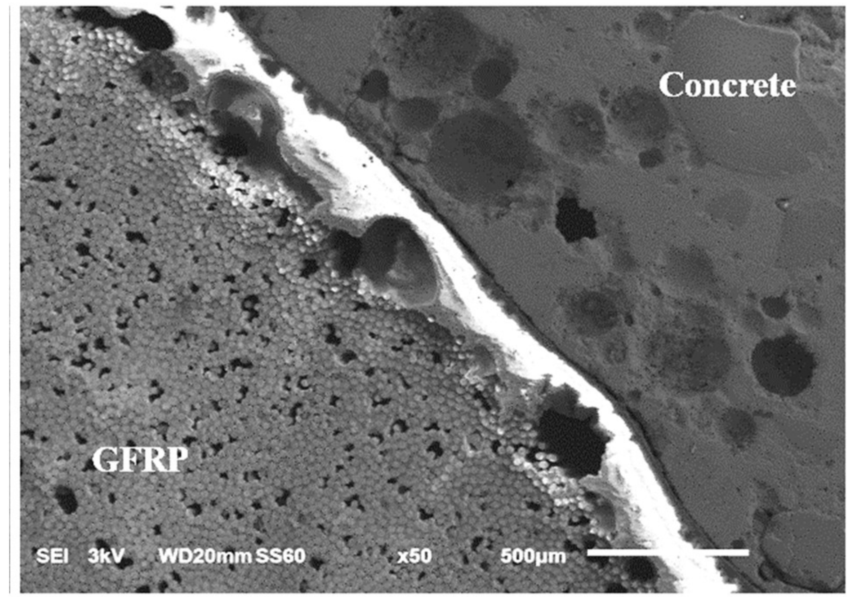
HOW DOES 'ACCELERATED' ACTUALLY COMPARE?

No sign of bond degradation nor loss of contact and mechanical properties after 15 years in service





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Source: Long-term Durability of GFRP Reinforcement in Concrete: A Case Study after 15 Years of Service - O. Gooranorimi, E. Dauer, J. Myers, A. Nanni

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BFRP …

Basalt fibers are composed of the minerals plagioclase, pyroxene, and olivine…

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EXISTING FRP MATERIAL OPTIONS & EVALUATION

	Pros	Cons
Vinyl Ester	• Industry standard for pultrusion • Free radical reaction leads to fast line speed	• Use of VOC (styrene)
Epoxy	• Zero VOC • Superior adhesive behavior	• Lack of comprehensive durability/engineering knowledge • Formulation development needed for line speed improvement
E-CR or R Glass Fiber	• Industry standard (90% GRP composites) • Abundant supply/ cost friendly	• Inferior tensile strength and modulus to S2-Glass
Basalt Fiber	▪ Similar tensile strength and modulus to E-Glass ▪ Potential lower price ▪ Single source material	• Lack of comprehensive durability/engineering knowledge • Sizing/ production technique needed for fiber handling

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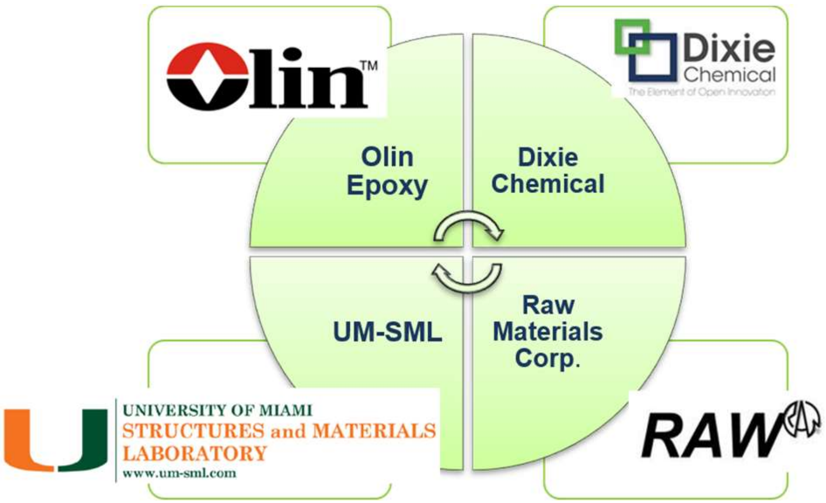
A COOPERATIVE EFFORT

Evaluate the performance of BFRP Epx/ANHYD rebars made by industrial production

Collect **alkaline resistance behavior** of BFRP Epx/ANHYD rebars by using standard testing methodology (ASTM)

Compare the data acquired from BFRP Epx/ANHYD rebars to those from GFRP and **enhance the comprehension** in long-term durability of BFRP rebars



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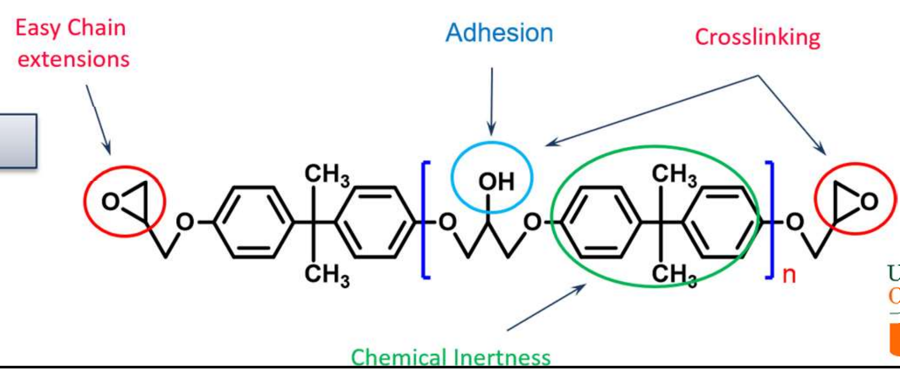
BFRP RESIN PROPERTIES

Property	Epoxy Resin	Pre-catalyzed Anhydride Hardener
Visc. @ 25°C [mPa.s] ASTM D445	11000 to 14000	75-150
Density @ 25°C [g/cm³] ASTM D4052	1.1-1.2	1.1-1.2
Shelf Life (months)	24	12
Parts by weight	100	92

Epoxy System Property	Value
Visc. @ 25 °C [mPa.s] ASTM D2983	500
Gel Time @ 23 °C [hrs] Gardner Standard Model Gel Timer	>24
Geltime @ 140 °C (secs) Gelnorm Gel Timer	98
Tg [°C] DSC, midpoint, 10 K/min	130-140
Tensile Strength [MPa] ASTM D638	90
Tensile Modulus [GPa] ASTM D638	3.2
Elongation at peak [%] ASTM D638	5.2
Flexural Strength [MPa] ASTM D790	114
Flexural Modulus [GPa] ASTM D790	2.2

Diglycidyl Ether Bisphenol A Epoxy Resin



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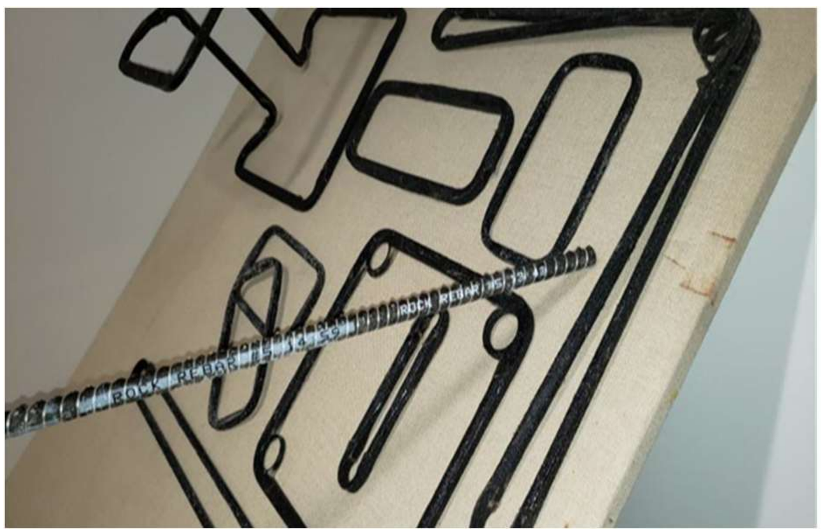
BFRP Epx/ANHYD rebars

- Pultruded BFRP rebars with post curing
- 3 sizes of rebars were tested with nominal diameters:
  - ✓ 0.109 in^2 (#3),
  - ✓ 0.207 in^2 (#4), and
  - ✓ 0.292 in^2 (#5)



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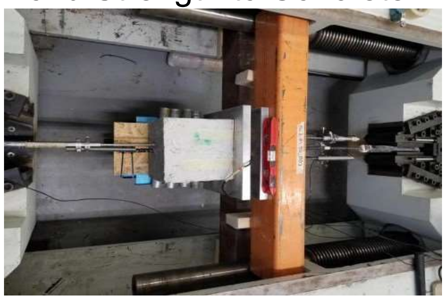
EXPERIMENT: TESTING METHODS

ASTM D7913
Bond Strength to Concrete

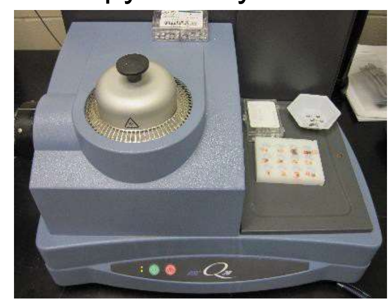


ASTM D7914 Bent Bar

ASTM D7205 Tensile Properties

ASTM D7617
Trans. Shear Behavior

ASTM E2160
Enthalpy of Polymerization



ASTM E2160
Glass Transition Temp.

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#5 BFRP REBAR: BEFORE ACCELERATED AGING

Methods	Test Description	REFERENCE	Test Values	Result
ASTM D7617	Guar. Transverse Shear Strength	>19 ksi	21.0 ksi	Pass
ASTM D2584	Fiber Content (by weight)	>70 %	79.8 %	Pass
ASTM D7205	Guar. Tensile Force	29.1 kip	33.1 kip	Pass
	Tensile Modulus of Elasticity	≥ 6.5 Msi	7.0 Msi	Pass
	Tensile Strain	≥ 1.1%	1.6 %	Pass
ASTM D792	Measured Cross Sectional Area	0.288 to 0.388 in^2	0.292 in^2	Pass
ASTM D570	Moisture Absorption Short Term	≤ 0.25 %	0.17 %	Pass
	Moisture Absorption Long Term	≤ 1.00 %	0.67 %	Pass
ASTM D7913	Guar. Bond Strength	>1100 psi	1227 psi	Pass
ASTM E2160	Degree of Cure	>95%	99.1 %	Pass
	Glass Transition Temperature (DSC)	>100 °C	139 °C	Pass

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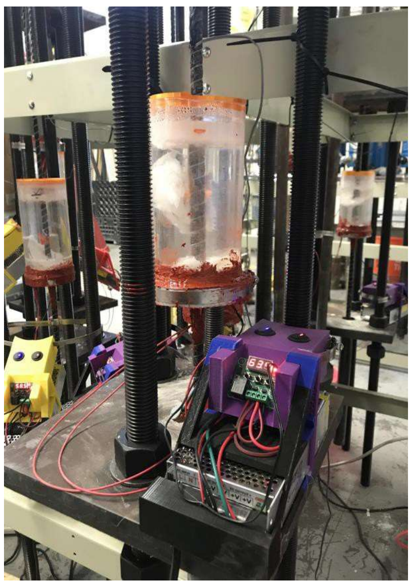
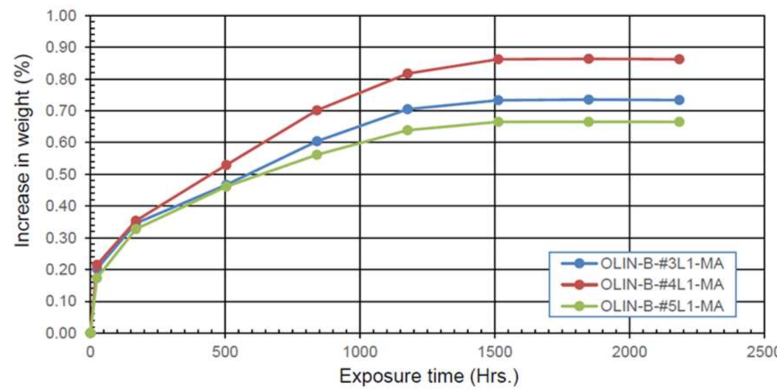
#5 BFRP REBAR: AFTER ACCELERATED AGING

- Post Alkaline Resistance per ASTM D7705 guideline, 90 days at 60 °C
- Saturated water adsorption after 90 days treatment





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#5 BFRP REBAR: AFTER ACCELERATED AGING

Test Method	Test Description	REFERENCE	Test Values	Result
SAMPLE #3				
ASTM D7205	Tensile Load Retention (with load)	>70 %	78.3 %	Pass
ASTM D7617	Trans. Shear Strength Retention	n/a	84.2 %	n/a
ASTM E2160	Degree of Cure	>95 %	99.06 %	Pass
	Glass Transition Temperature (DSC)	>100 °C	139 °C	Pass
SAMPLE #4				
ASTM D7705	Tensile Load Retention (with load)	>70%	92.3 %	Pass
ASTM D7617	Trans. Shear Strength Retention	n/a	107.6 %	n/a
ASTM E2160	Degree of Cure	>95 %	99.4 %	Pass
	Glass Transition Temperature (DSC)	>100 °C	128 °C	Pass
SAMPLE #5				
ASTM D7705	Tensile Load Retention (with load)	>70 %	89.8 %	Pass
ASTM D7617	Trans. Shear Strength Retention	n/a	106.2 %	n/a
ASTM E2160	Degree of Cure	>95 %	99.1 %	Pass
	Glass Transition Temperature (DSC)	>100 °C	139 °C	Pass

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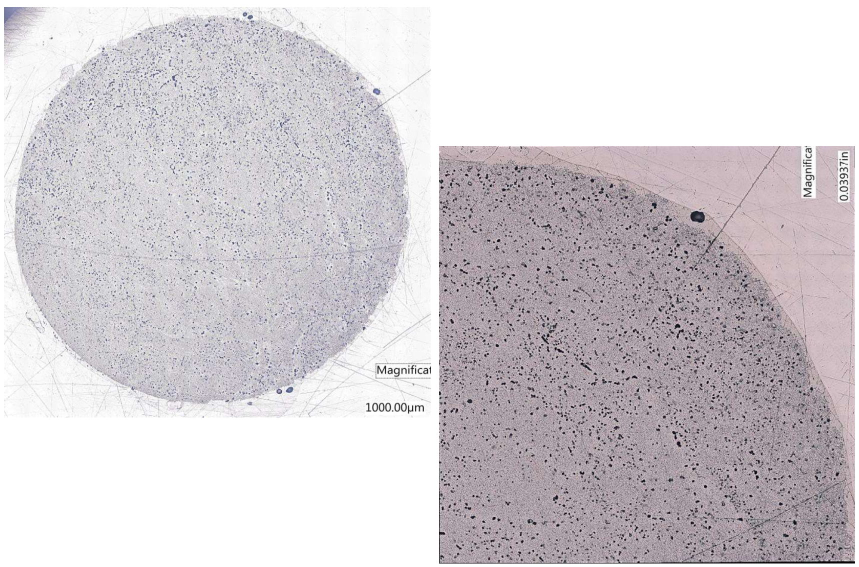
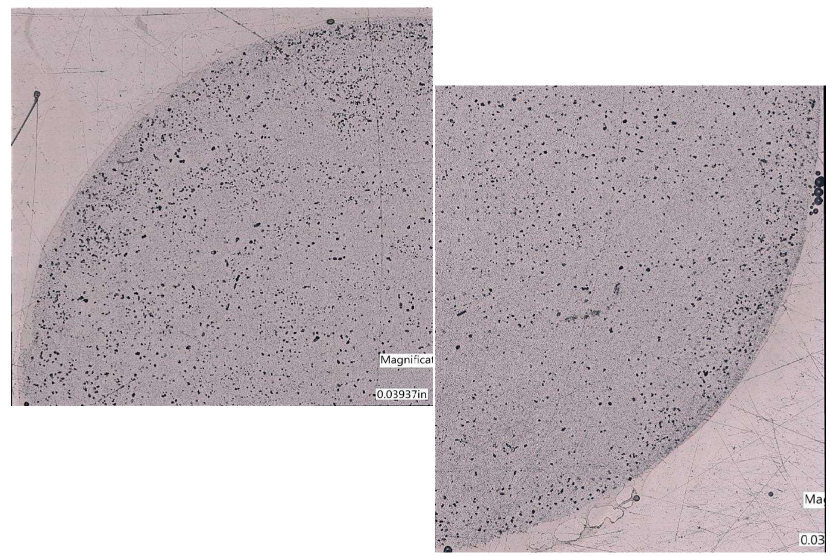
SEM INVESTIGATIONS

No noticeable degradation was observed under SEM imaging



Sample #5 Before Aging



Sample #5 After Aging

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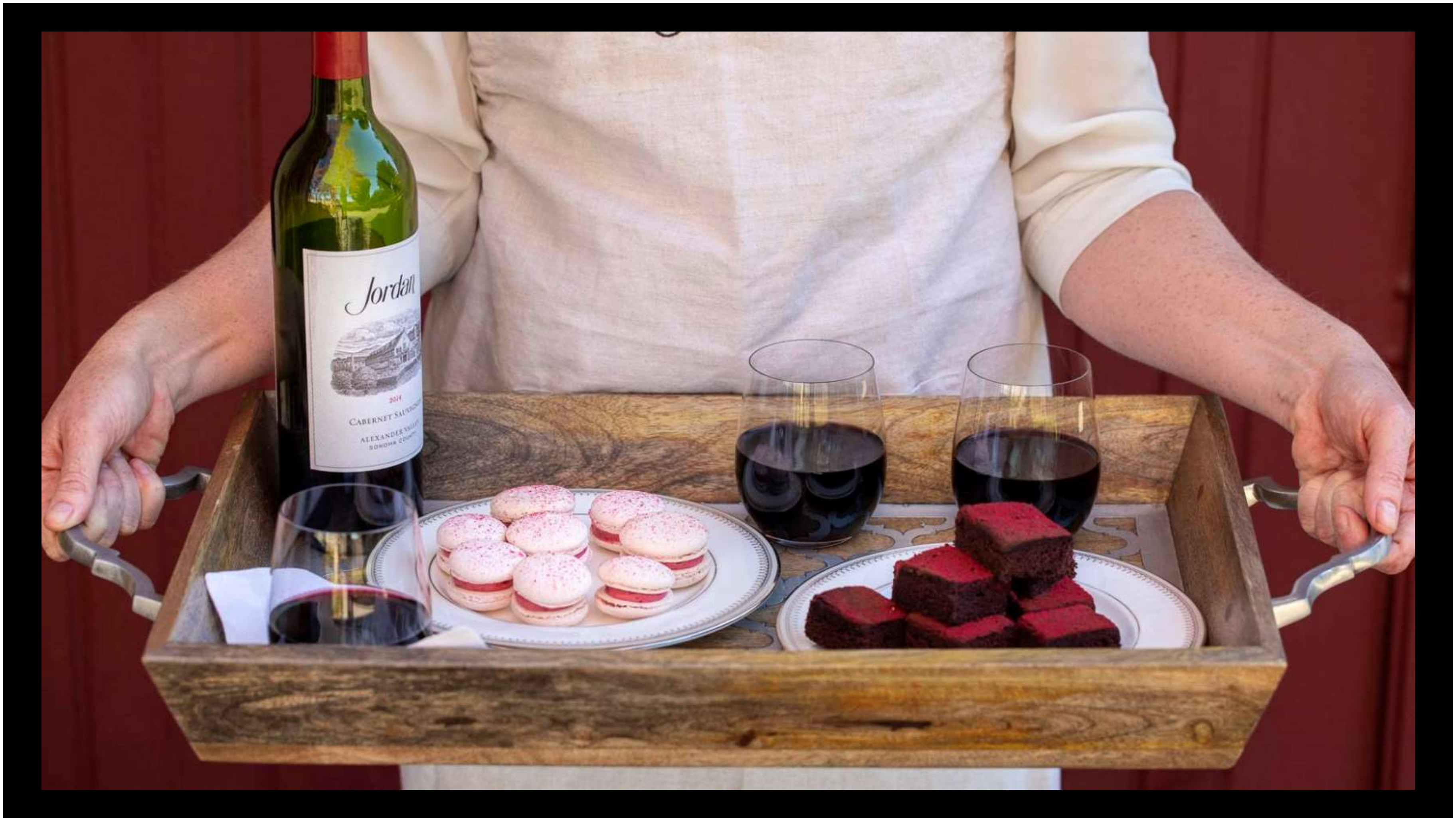

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SUMMARY

- Nominal #3, #4 and #5 BFRP rebars were made with the Epx/ANHYD (epoxy-anhydride) pultrusion system by industrial production
- A thorough study on those BFRP rebars was conducted at UM-SML (University of Miami, Structures and Materials Laboratory), an ISO 17025 accredited and FDOT (Florida Department of Transportation) qualified testing facility
- The durability performance was evaluated through an accelerated environmental treatment that involved a 90-day immersion in alkaline solution at 60 ^{o}C under a sustained load.

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CONCLUSIONS

- Prior to the accelerated environmental treatment, the BFRP rebars exhibit physical-mechanical properties that meet or exceed existing minimum specifications for GFRP (glass FRP rebar).
- Post aging exposure results for three different bar sizes indicate that the BFRP rebars possess higher tensile load retention (78%-92%) than the available requirement, rebars (>70%).
- Transverse Shear results indicates adequate thermoset protection
- Overall, the testing outcomes suggest BFRP Epx/ANHYD is capable providing safe and reliable rebars for infrastructure applications

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BFRP KNOWLEDGE-GAPS

	Pros	Cons
Vinyl Ester	• Industry standard for pultrusion • Free radical reaction leads to fast line speed	• Use of VOC (styrene)
Epoxy	• Zero VOC • Superior adhesive behavior	• Lack of comprehensive durability/engineering knowledge • Formulation development needed for line speed improvement
E-CR or R Glass Fiber	• Industry standard (90% GRP composites) • Abundant supply/ cost friendly	• Inferior tensile strength and modulus to S2-Glass
Basalt Fiber	▪ Similar tensile strength and modulus to E-Glass ▪ Potential lower price ▪ Single source material	• Lack of comprehensive durability/engineering knowledge • Sizing/ production technique needed for fiber handling

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BFRP KNOWLEDGE-GAPS

- Basalt fiber specification
- Basalt rock (raw material) sourcing
- Clearing the misinformation: initial BFRP rebar vs today's manufacturing
- Economies of scale needed: industrial size production
- Sizing / production for basalt fiber for handling may need refinement

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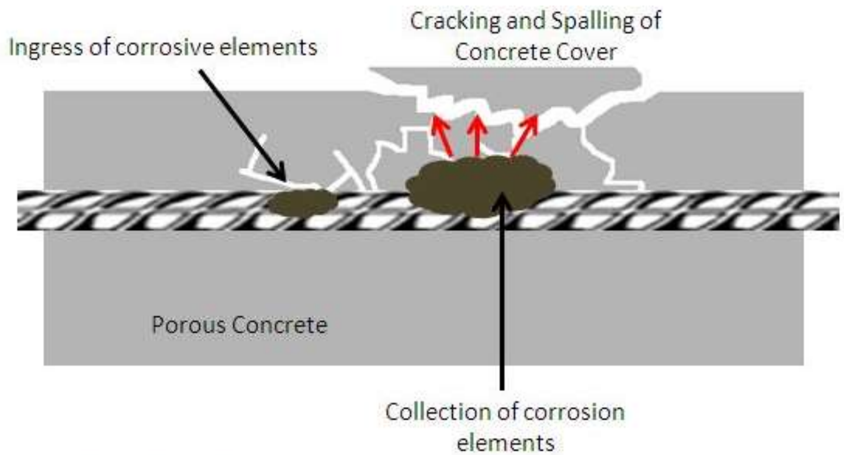
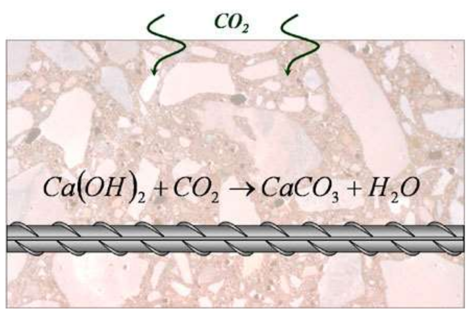
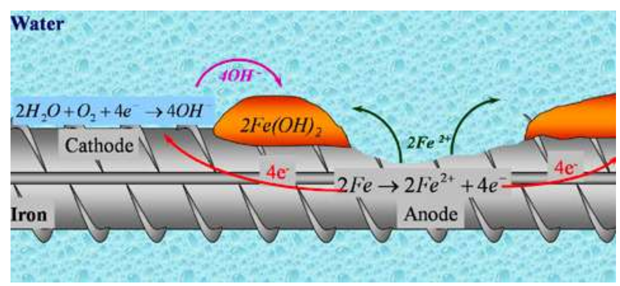
FRP REBAR KNOWLEDGE-GAPS

STEEL Rebar corrosion mechanism







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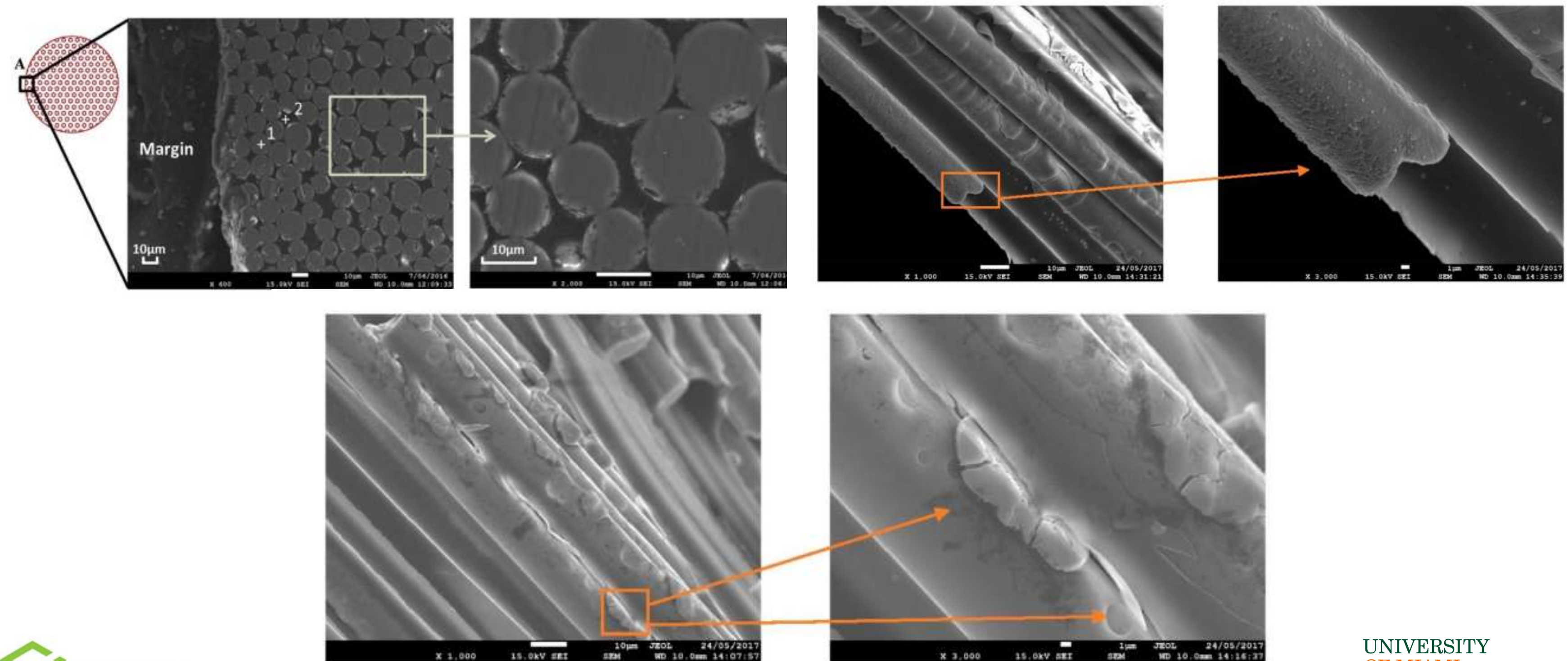
FRP REBAR KNOWLEDGE-GAPS

FRP Rebar Degradation Mechanism



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Raman, R. K., et al. "Understanding fibre-matrix degradation of FRP composites for advanced civil engineering applications: an overview." *Corrosion and Materials Degradation* 1.1 (2020): 27-41.

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FRP REBAR KNOWLEDGE-GAPS

FRP Rebar Degradation Mechanism

Degradation of the shell formation and pitting of basalt fibers due to exposure to alkaline environment, as a result of the reaction of alkali-ions with silicate in fibers:

$$\equiv Si - OR + \left(H^{+} + OH^{-}\right) \rightarrow \equiv Si - OH + ROH$$

Rybin, V.; Utkin, A.; Baklanova, N. Corrosion of uncoated and oxide-coated basalt fibre in different alkaline media. Corros. Sci. 2016, 102, 503–509.

Further destruction and dissolution of silicate network of fibers may progress per:

$$\equiv Si - O - Si \equiv + \left(R^{+} + OH^{-}\right) \rightarrow \equiv Si - OH + RO - Si$$

Lipatov, Y.V.; Gutnikov, S.; Manylov, M.; Zhukovskaya, E.; Lazoryak, B. High alkali-resistant basalt fiber for reinforcing concrete. Mater. Des. 2015, 73, 60–66.

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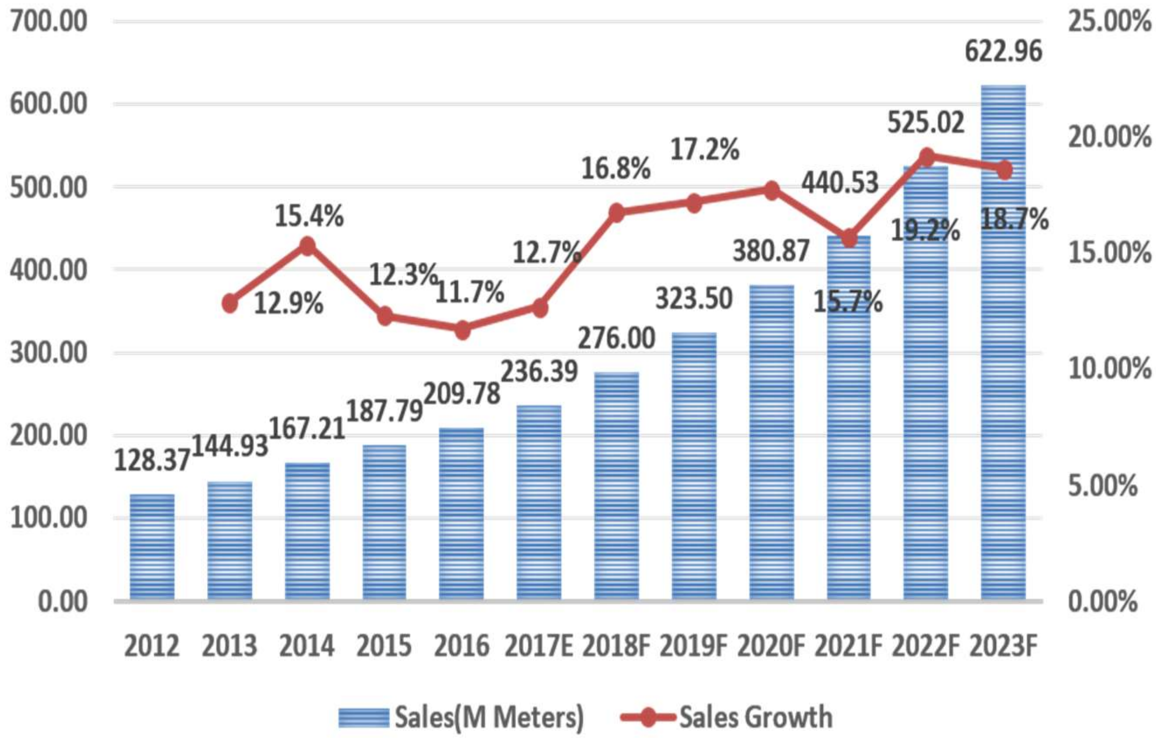
Opportunity
2021

GLOBAL FRP REBAR SALES & GROWTH RATE…



Purchased Market Report, 2017, QY Research Publishing

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GLOBAL FRP REBAR SALES & GROWTH RATE…

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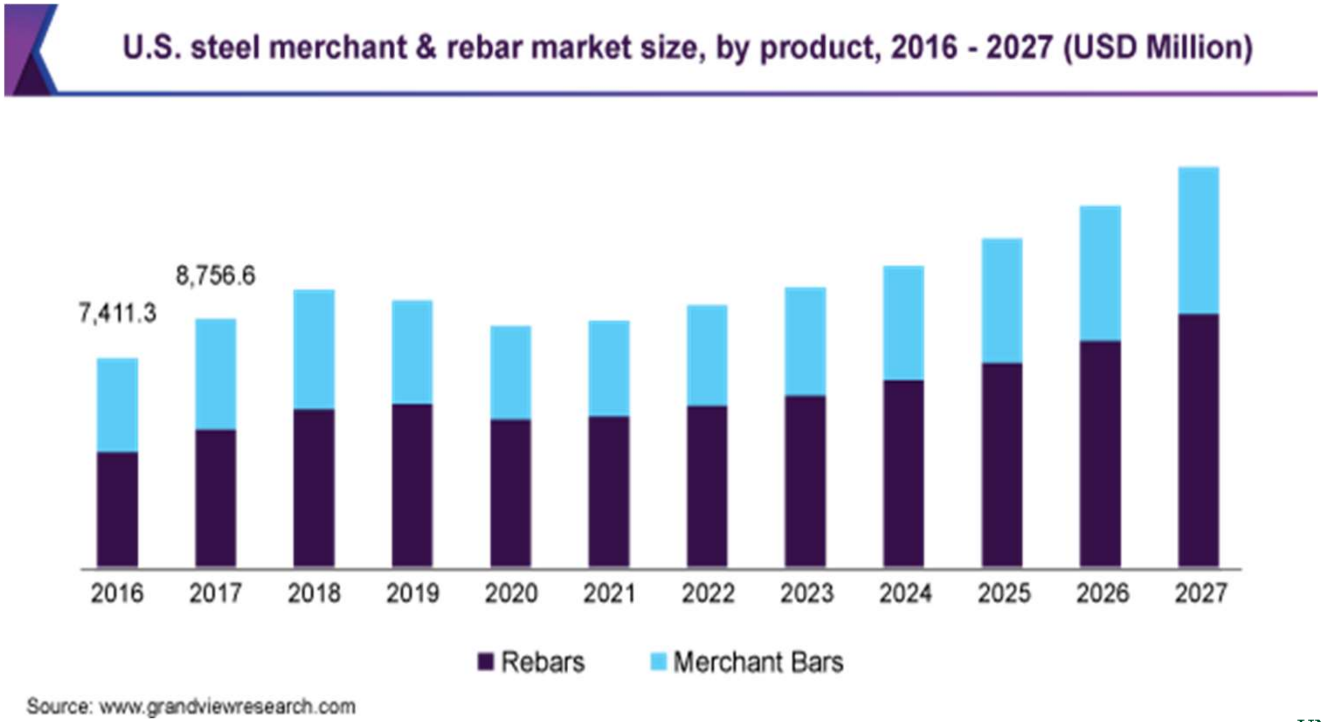
STEEL MARKET…



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The Halls River Bridge (full scale project, in Homassassa FL)

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OPPORTUNITY

Test segments on the embankment located at tidal range contain BFRP rebars…

…due for extraction in the future

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OPPORTUNITY

- New resin systems (Thermoplastics) available
- Increasing number of FRP rebar manufactures (pultruders)
- Increasing number of projects specifying FRP bars

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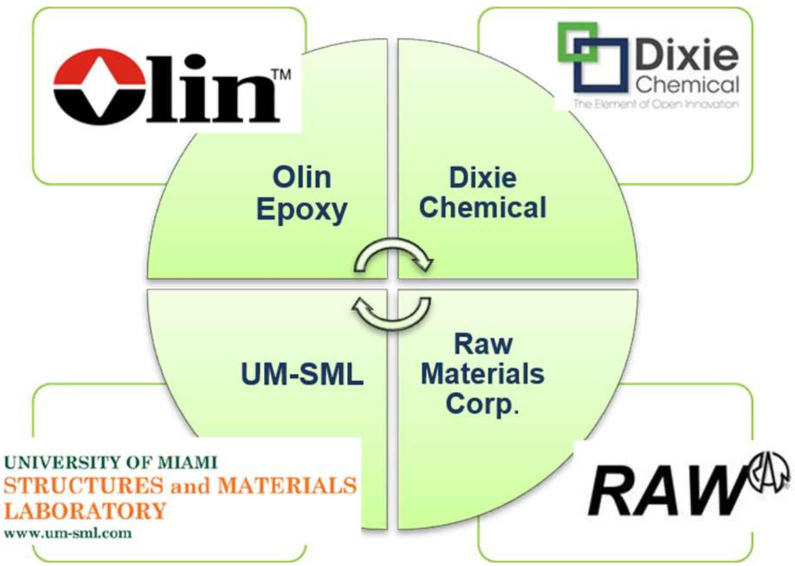
ACKNOWLEDGEMENTS



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DURABILITY STUDY OF EPOXY-BASALT FIBER COMPOSITE REBAR FOR CONCRETE REINFORCEMENT

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