Florida A&M University-Florida State University

College of Engineering

BE694 - Testing Protocol and Material Specifications for Basalt Fiber Reinforced Polymer Bars

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Presentation Outline

- Project Overview
- Project Benefits
- Implementation Items
- Introduction
- Background
- Project Objectives
- Task Outline
- Summary
- Further Recommendations
- Future Research
- Closing Remarks

Project Overview

Project Overview

Project Overview

BFRP Rebars and its Components

Resin Basaltic Rocks Basalt Fiber BFRP Rebar

Project Benefits

Project Benefits

Qualitative

- Implementation of innovative materials
  - To enhance the sustainability and durability of the infrastructure
- Evaluation of alternative corrosion resistant reinforcement for concrete
- Identification of viable raw material sources for Basalt FRP rebars
- Assessment of constituent materials for BFRP composites
- Addition material alternatives generate more market competition

Project Benefits

Quantitative

- Acquisition of experimental results for basalt rebar products
- Characterization of specific BFRP rebar types
- Defined acceptance criteria for Basalt FRP rebars
- Potential service life extension of structures and infrastructure in costal regions
- Reduction of maintenance cost
- Additional material options improve supply chain redundancy

Implementation Items

Implementation Items

Application of BFRP Rebars

- Update design guidelines
  - FDOT Section 932
- Share findings with industry
  - FRP Rebar Council

Introduction

Introduction

Corrosion and Durability

- Steel corrosion $\Rightarrow$ main deteriorating mechanisms for infrastructure components
    - Reduces lifespan of reinforced concrete (RC)
- Particularly concerning in costal regions
    - Crucial concrete structures directly exposed to aggressive environments
- To enhance durability, FDOT continues to implement innovative materials

Introduction

Fiber Reinforced Polymer (FRP) Rebars

- Technological advancements have facilitated the use of FRP rebars
  - For internal reinforcement of concrete
- Viable alternative to traditional steel reinforcement due to significant advantages:
  - Light, strong, magnetic transparence, and corrosion resistant
- May lead to more durable concrete members and extended structural life

Introduction

Current FDOT Regulation

- FDOT regulates Nonmetallic accessory materials for concrete in FDOT Section 932

- Section 932-3 regulates glass and carbon FRP materials
  - BFRP now addressed, through this (and previous) project

- BFRP currently not allowed for submerged applications

Project Subject Background

Project Subject Background

Emerging Materials

- Different fiber types exist
  - Glass (GFRP), carbon (CFRP), aramid (AFRP), basalt (BFRP)
- Until recently, basalt FRPs have not been produced/used in US
  - For historic reasons
- Now, BFRP rebars are produced and are available in US market

Project Subject Background

Basalt Rock, Basalt Fiber, and Basalt Rebar

Project Subject Background

Problem Statement

- Production of FRP rebars is not standardized
- No acceptance criteria for basalt FRP rebars
- Inferior BFRP products are reportedly available on the world market now
- Urgent need for robust material standards and acceptance criteria
  - To guarantee safe use of new technology

Project Subject Background

Problem Statement

- FRP rebars are composite materials
  - Fiber + Sizing + Resin = Rebar

- No material standard available that relates constituents to final rebar quality
  - Raw materials or production quality vs. rebar performance and durability/service life

Project Objectives

Project Objectives

Research Goals — Raw Materials

- Evaluate basalt fiber quality
- Define minimum requirements for fiber (Similar to ASTM D 578)
  - Strength and resistance to chemicals
- Analyze fiber sizing (if possible)
  - For proper interfacial bond (to basalt fibers and resin)
- Identify high performance resin matrix
  - Compatibility with appropriately sized basalt fibers

Project Objectives

Research Goals — BFRP Rebars

- Identify commonly available BFRP rebar products
    - For performance evaluation
- Evaluate virgin material properties for material characterization
- Age material in various aggressive environments
    - To measure strength retention properties
- Evaluate potential degradation mechanism to quantify service-life

Task Outline

Task Outline

Activities

- This project consists of nine tasks

  - Preparations for Experiments: Tasks 1-2
  - Experiments: Tasks 3-6
  - Recommendations for BFRP Specifications: Task 7
  - Project Conclusion: Tasks 8-9

Task Outline

Preparation for Experiments

- Task 1: Literature Review
  - Conduct a comprehensive review to include the following:
    - FRP rebar basics
    - Basalt fiber types
    - Sizing for basalt fibers
    - Suitable resin types
    - Basalt FRP rebars

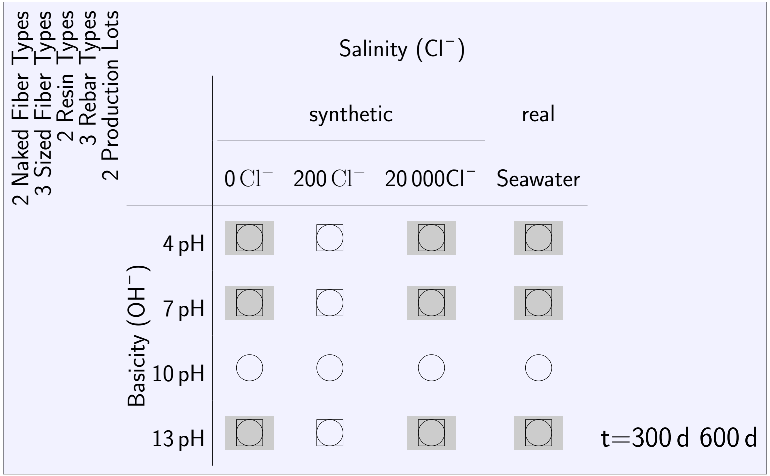
Task Outline

Preparation for Experiments

- Task 2: Material Characterization and Testing Plan
  - The following activities were conducted:
    - Suitable constituent materials were identified
    - Suitable BFRP rebar products were determined
    - Exposure and test conditions were defined
    - A research test matrix was developed

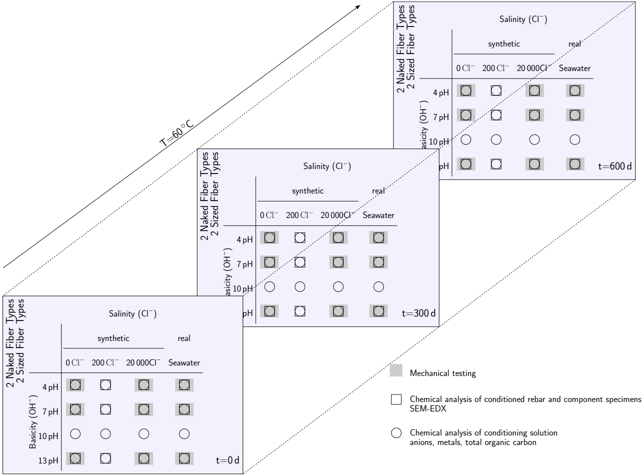
Task Outline

General Test Matrix for Chemical Exposure



Task Outline

Test Concept for Chemical Exposure



Task Outline

Types of Sample

- BFRP rebars
  - Three different rebar types (Type A, B and C)
  - Two production lots and two different sizes (# 3 and # 5)
- Fibers
  - Two different unsized fiber types (Type A and B)
  - Three different sized fiber types (Type A, B and C)
- Resins
  - Epoxy (Type A)
  - Vinyl Ester (Type B)

Task Outline

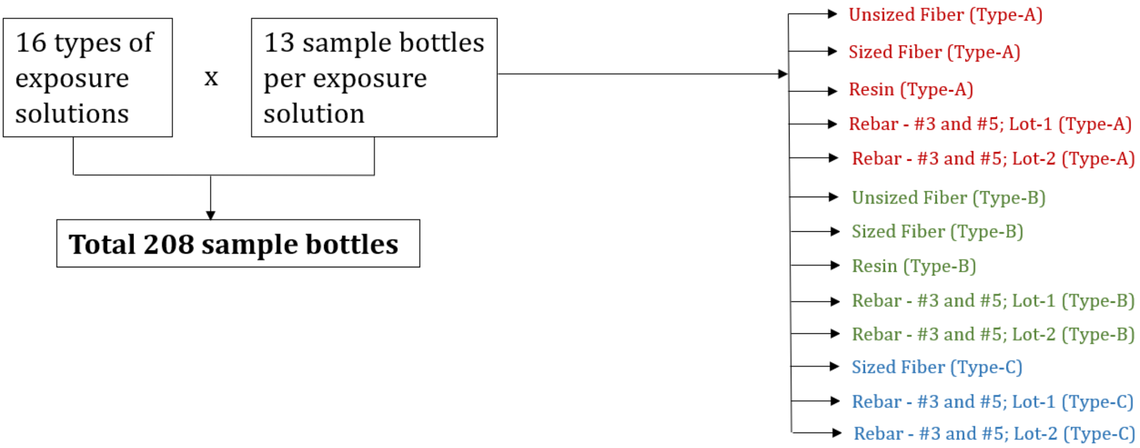
Specimens in Environmental Chamber, exposed to 60°C Temperature

Before Exposure

After Exposure

Task Outline

Exposure Solution Breakdown with Specimens

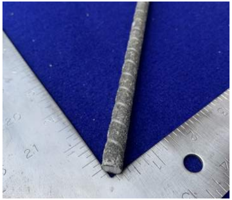


Task Outline

Chemical Tests on Exposure Solutions

	Exposure Solutions Containing			
Test type	Unsized Fibers	Sized Fibers	Resins	BFRP Rebars
pH	✓	✓	✓	✓
Dissolved Oxygen	✓	✓	✓	✓
Salinity	✓	✓	✓	✓
Alkalinity	✓	✓	✓	✓
Anions (Chloride and Sulfate)	✓	✓	✓	✓
Metals (Na, K, Ca, Mg, Fe, Al, Cr and Si)	✓	✓	✓	✓
Total Organic Carbon	✓	✓	✓	✓
Bisphenol-A	✗	✗	✓	✓

Task Outline



(a) Type A #3

(b) Type B #3

(c) Type C #3

(a) Type A #5

(b) Type B #5

(c) Type C #5

Task Outline

Physical tests on rebar

		Specimen count	
Test type	Test method	Per sample	Total†
Cross-sectional area	ASTM D792	5	60
Fiber content	ASTM D2584	5	60
Moisture absorption	ASTM D570	5	60
Glass transition temperature	Differential scanning calorimetry	2	216

† 60 specimens: Test matrix has 3 types of rebars, 2 lots, 2 sizes.

† 216 specimens: Test matrix has 3 types of rebars, 2 lots, 2 sizes and 9 exposure types.

Task Outline

Mechanical tests on rebar

		Specimen count	
Test type	Test method	Per sample	Total†
Tensile strength	ASTM D7205	3	648
Transverse shear strength	ASTM D7617	5	1080
Apparent horizontal shear strength	ASTM D4475	5	1080
Bond-to-concrete	ACI440.3R,B.3	3	648

† 648 specimens: 3 types of rebars, 2 lots, 2 sizes, 9 exposure types, 2 durations.

† 1080 specimens: 3 types of rebars, 2 lots, 2 sizes, 9 exposure types, 2 durations.

Task Outline

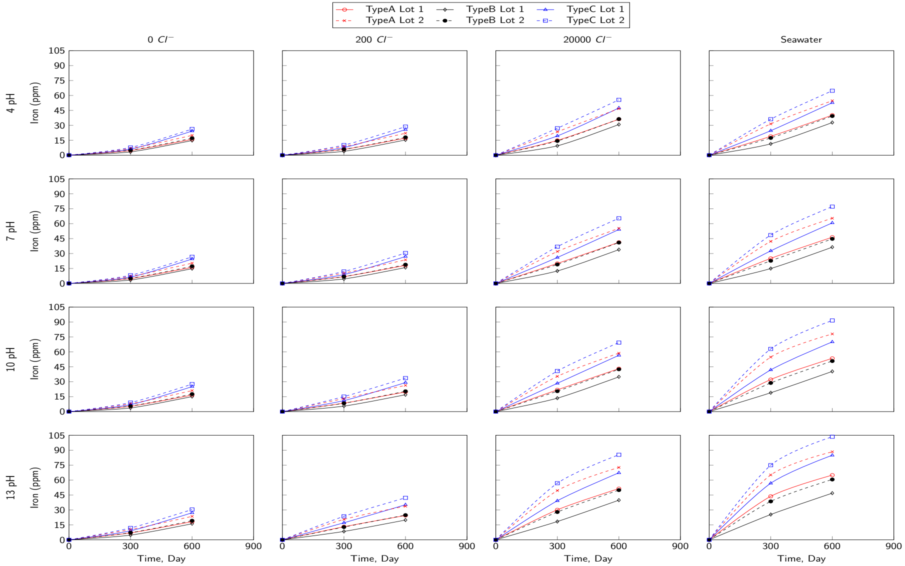
Experiments

- Tasks 3-6: Report performance of constituents and BFRP rebar products
  - According to test matrix $\Rightarrow$ Exposure conditions, strength tests, etc.

- Task 3: Basalt Fiber Characterization and Performance
- Task 4: Sizing Characterization and Performance
- Task 5: Resin Matrix Characterization and Performance
- Task 6: BFRP rebar Characterization and Performance

Task Outline

BFRP Rebar Degradation: Metals — Iron Content vs Exposure Time — All Rebar Sample Groups



Task Outline

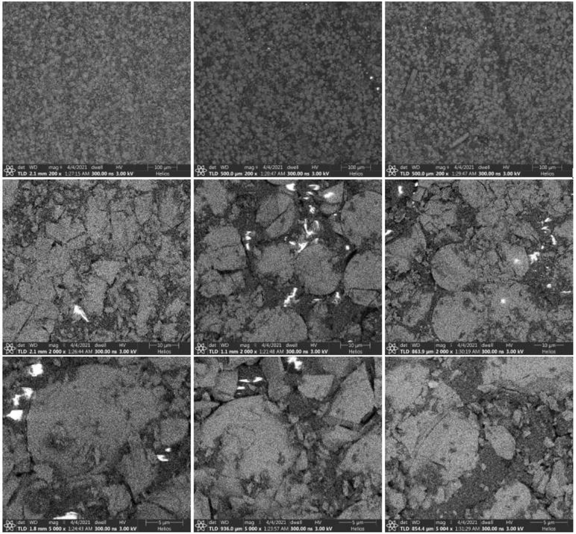
SEM Image Analysis — Unexposed — Lot 1 Rebars

Type A | Type B | Type C

200 X

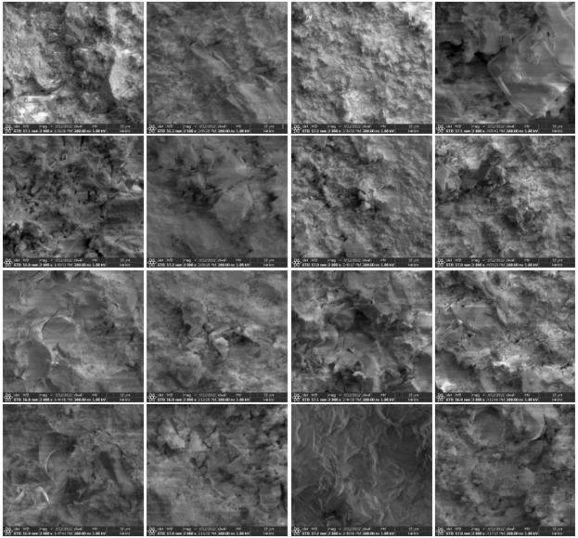
2000 X

5000 X



Task Outline

SEM Image Analysis — After 300 Days — Lot 1 Type B Rebars — At 2000x

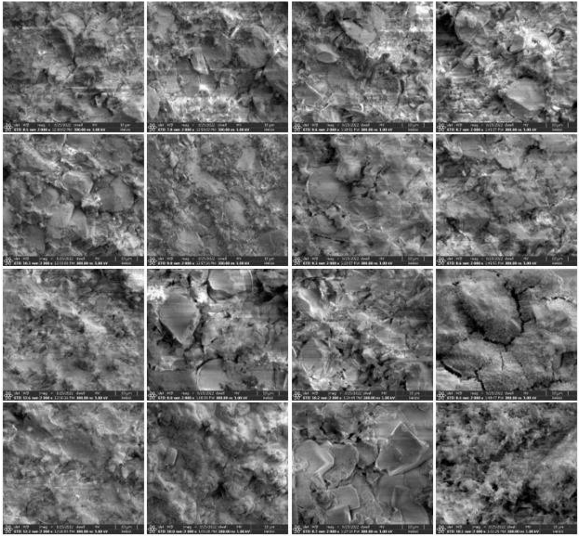


Task Outline

SEM Image Analysis — After 600 Days — Lot 1 Type B Rebars — At 2000x

Cl^-0 | Cl^-200 | Cl^-20000 | Seawater

pH 4
pH 7
pH 10
pH 13



Task Outline

Physical and mechanical tests on Type A # 3 rebars

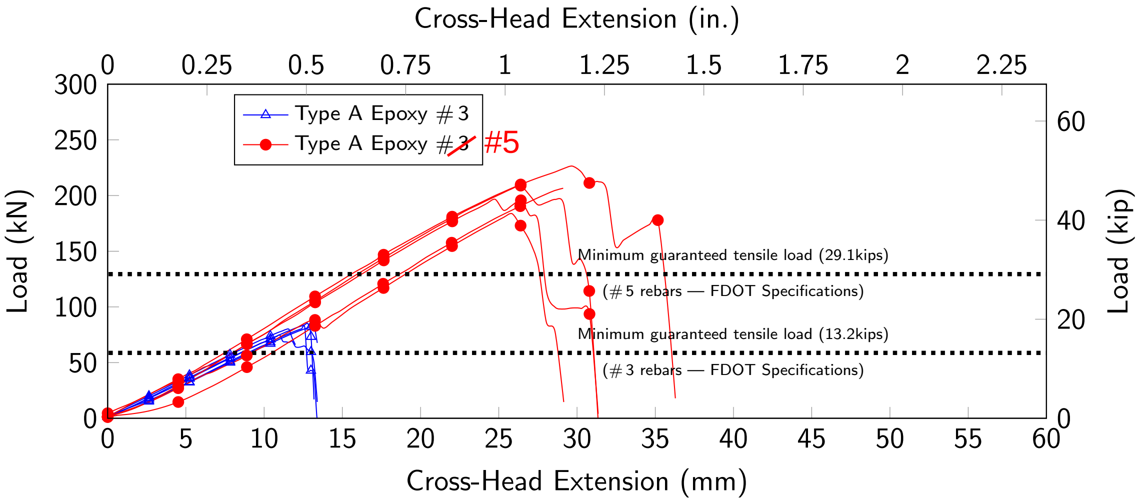
			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross-Sectional Area	in.^{2}	0.11	0.15	0.104 – 0.161	✓	0.104 – 0.161	✓	0.104 – 0.161	✓
ASTM D 2584	Fiber Content	% wt.	75.17	75.17	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓
ASTM D 570	Moist. Absorption Short Term @50 °C	%	0.2	0.2	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓
ASTM D 570	Moist. Absorption Long Term @50 °C	%	0.55	0.55	$\leqslant 1.0$	✓	n/a	n/a	$\leqslant 1.0$	✓
ASTM E 1356	Glass Transition Temperature	°F	241	241	$\geqslant 212$	✓	$\geqslant 212$	✓	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	29.1	n/a	$\geqslant 22$	✓	$\geqslant 22$	✓	$\geqslant 19$	✓
ASTM D 4475	Horizontal Shear Stress	ksi	5.75	n/a	n/a	n/a	$\geqslant 5.5$	✓	n/a	n/a
ASTM D 7205	Min. Guaranteed Tensile Load	kip	13.4	13.4	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓	$\geqslant 13.2$	✓
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	121.7	105.2	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	7306	6313	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓
ASTM D 7205	Max. Strain	%	1.66	1.66	n/a	n/a	n/a	n/a	n/a	n/a
ACI440. 3 R,B.3	Bond-to-Concrete Strength	ksi	3.20	2.64	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓

Task Outline

Physical and mechanical tests on Type A #5 rebars

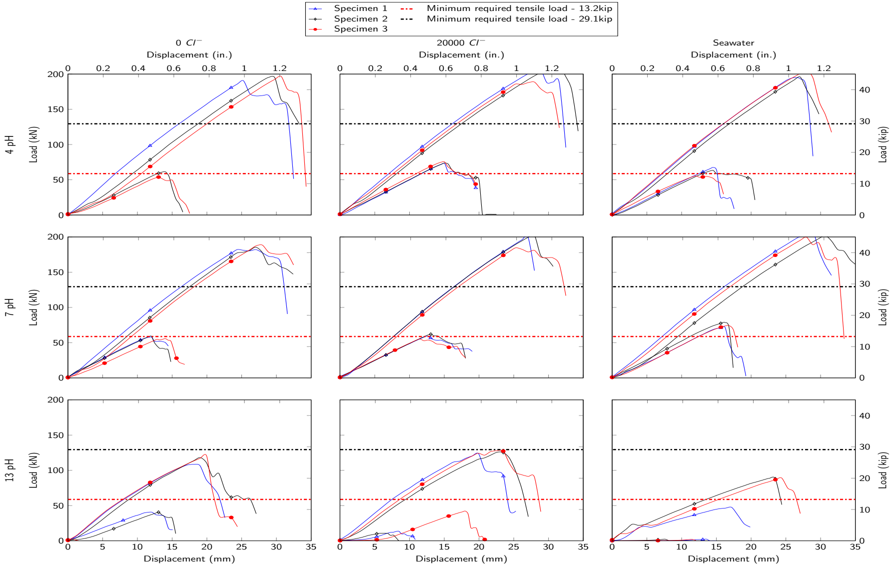
			Per diameter		FDOT 932-3/2017		AC454		ASTM D 7957	
Test Method	Test Description	Unit	Nom.	Exp.	Criteria	✓/✗	Criteria	✓/✗	Criteria	✓/✗
ASTM D 792	Measured Cross-Sectional Area	$in.^2$	0.307	0.25	0.288 – 0.388	✓	0.288 – 0.388	✓	0.288 – 0.388	✓
ASTM D 2584	Fiber Content	% wt.	78.4	78.4	$\geqslant 70$	✓	$\geqslant 70$	✓	$\geqslant 70$	✓
ASTM D 570	Moist. Absorption Short Term @50 °C	%	0.18	0.18	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓	$\leqslant 0.25$	✓
ASTM D 570	Moist. Absorption Long Term @50 °C	%	0.77	0.77	$\leqslant 1.0$	✓	n/a	n/a	$\leqslant 1.0$	✓
ASTM E 1356	Glass Transition Temperature	°F	241	241	$\geqslant 212$	✓	$\geqslant 212$	✓	n/a	n/a
ASTM D 7617	Min. Guaranteed Transverse Shear	ksi	25.7	n/a	$\geqslant 22$	✓	$\geqslant 22$	✓	$\geqslant 19$	✓
ASTM D 4475	Horizontal Shear Stress	ksi	6.22	n/a	n/a	n/a	$\geqslant 5.5$	✓	n/a	n/a
ASTM D 7205	Min. Guaranteed Tensile Load	kip	41.2	41.2	$\geqslant 29.1$	✓	$\geqslant 32.2$	✓	$\geqslant 29.1$	✓
ASTM D 7205	Min. Guaranteed Tensile Strength	ksi	137.9	121.0	n/a	n/a	n/a	n/a	n/a	n/a
ASTM D 7205	Tensile Modulus	ksi	7749	6989	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓	$\geqslant 6,500$	✓
ASTM D 7205	Max. Strain	%	1.78	1.78	n/a	n/a	n/a	n/a	n/a	n/a
ACI440. 3 R,B.3	Bond-to-Concrete Strength	ksi	3.33	2.89	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓	$\geqslant 1.1$	✓

Task Outline



Task Outline

Tensile strength test — Load vs Displacement — Type B



Task Outline

Recommendations for BFRP Specifications

- Task 7: Proposed BFRP rebar Specification
  - Recommend suitable acceptance criteria for BFRP rebars
  - Suggest updates to FDOT Section 932

Task Outline

Recommendations for BFRP Specifications

- Virgin BFRP Rebar Performance acceptable
  - Appears stronger than GFRP, but with significant variation
- For now, define BFRP acceptance criteria in line with GFRP acceptance criteria
- Durability evaluations in high alkalinity and salinity environments not conclusive
  - Limit submerged applications of BFRP rebars
    - Further research need on applicability of accelerated aging
    - Saturated rebar vs. pore solution (high pH) at the rebar surface

Task Outline

Experiments

- Task 8a: Draft Final Report
  - Provide comprehensive report to document Tasks 1 through 7
- Task 8b: Closeout teleconference
  - Discuss final review comments and report changes
- Task 9: Final Report
  - Complete report based on discussion in Task 8

Task Outline

Environmental reduction factor (C_E)

- Strength degradation following long-term exposure to aggressive environments

$$f_f d = C_E . f'_{fu} \tag{1}$$

- $f_f d$: design strength
- $f'_f u$: specified strength

Task Outline

Environmental reduction factors — International design guidelines

- fib: 0.55
- CSA: 1.0
- ACI: 0.7
- AASHTO: 0.7

Task Outline

C_E — Refined approach — fib bulletin 40

$$C_E = \frac{\frac{f_{fk1000h}}{f_{f0}}}{\left(\frac{100-R_{10}}{100}\right)^n} \tag{2}$$

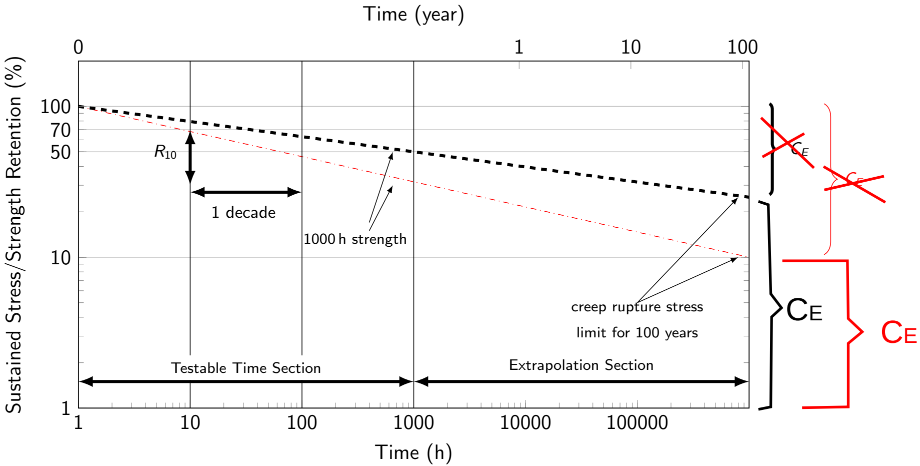
$$n = n_{mo} + n_T + n_{SL} + n_d \tag{3}$$

$$C_E = \frac{1}{\left(\frac{100-R_{10}}{100}\right)^{n+2}} \tag{4}$$

f_{f0}:	strength at day 0
$f_{fk1000h}$:	1000 h strength
n:	the sum of influence terms
R_{10}:	the standard reduction of strength per logarithmic decade
n_{mo}:	the term for moisture condition
n_T:	the term for temperature
n_d:	the term for diameter correction factor

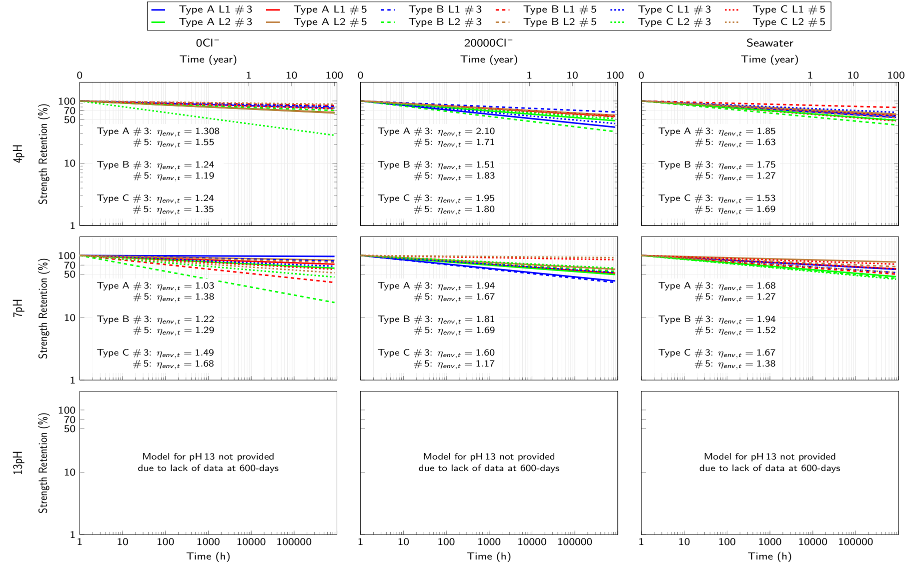
Task Outline

Strength retention based on stress rupture



Task Outline

BFRP long-term tensile strength retention



Summary of Research Conclusions

Summary of Research Conclusions

Chemical Tests — Alkalinity

- Alkaline environments lead to more degrading effects than acidic or neutral situation
- The presence of iron differentiates BFRP from GFRP
  - Iron oxide primarily separates BFRP rebars from the GFRP rebar
  - Degradation mechanism appears to be closely related
- Alkali-silica reaction is one of the main causes for the degradation of GFRP and BFRP bars
  - A reactive layer was formed due to the dissolution of the silica network (Si–O)
  - Si–OH gel appeared on the surface of the fibers
- Hydroxyl ($OH-$) ions from the alkaline solution attacked basalt fibers
  - The silica network (Si–O–Si–) in the basalt fibers break down
  - Neutral and acid environments do not attack the silicon lattice bond

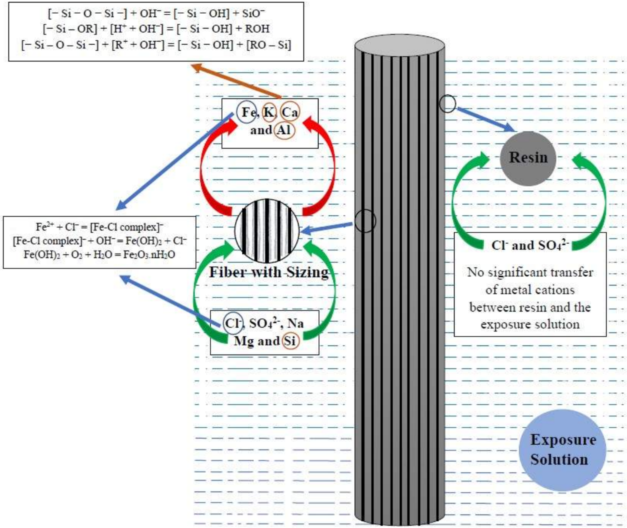
Summary of Research Conclusions

Chemical Tests — Salinity

- In saline rich environments, basalt fibers degrade faster
  - Because molecules (H_2O) and ions (Cl^- and Na^+) penetrate the surface
  - Forming voids and oxides (iron oxide) which react with (Fe^{2+}) and OH^-
- During immersion, H_2O, O_2, CO_2 molecules and Cl^-, Na^+ ions penetrated the resin
  - Through channels or voids
  - Reactions with Cl^- and (Fe^{2+}) ultimately leads to corrosion on the BFRP surface
  - Clearly visible during SEM analyses

Summary of Research Conclusions

Chemical Transfer Direction between solid samples and exposure solution (for Seawater Environment)



Summary of Research Conclusions

Chemical Tests — Fibers and Sizing

- Sized and unsized fibers degraded in harsh environments
  - High salinity and pH environments lead to more severe degradation
  - 13 pH seawater lead to most degradation due to a high concentration of sulfate ion
- Sizing material leached completely into aging solution (at later age)
  - As comparison between sized and unsized fibers showed
- Type A and C fibers degraded more than Type B fibers

Summary of Research Conclusions

Chemical Tests — Resin Matrix

- Neat Resin samples did not degrade severely
  - While slight degredation was visible in SEM analysis, the sample remained in tact
- Resin aging lead to a decrease of pH and alkalinity in exposure solution
  - In some (not all) cases
- The metal concentration of the exposure solution did not change over time
  - Due to the organic nature of Resin $\Rightarrow$ mostly carbon (C), hydrogen (H) and oxygen (O)
- Type A resin degraded more than Type B resin

Summary of Research Conclusions

Mechanical Tests

- Rebar performance appeared to be closely related to its moisture absorption property
  - Moisture absorption behavior is inherently related to the rebar porosity

- Rebars with higher porosity degraded more during aging

- Transverse shear strength: BFRP rebars $>>$ GFRP rebars
  - Bars even passed GFRP minimum criteria after exposure to all 4 and 7 pH environments

Summary of Research Conclusions

Mechanical Tests

- The apparent horizontal shear strength is resin-driven
    - Not significantly different from measurements usually obtained for GFRP products
- FDOT Specifications Section 932 should maintain the minimum threshold value
    - Quality control parameter

Summary of Research Conclusions

Mechanical Tests

- The tensile strength of virgin BFRP rebars is hight than the strength of GFRP rebars
- BFRP rebars surpasses the maximum tensile strain of glass fiber based rebars
- Aged rebars exposed to 4 and 7 pH environments acceptably retained strength
  - More than 75 % of their initial strength after 300 d of exposure
  - More than 60 % of the initial strength after 600 d exposure
- Most BFRP rebars exposed to 13 pH at 60 °C for 600 days disintegrated
  - Could not be tested
  - If tested, no significant strength was maintained

Summary of Research Conclusions

Mechanical Tests

- The bond-to-concrete strength appears to be driven by geometric features
  - According to the surface enhancement and not by the fiber type
  - BFRP rebars showed similar behavior as GFRP rebars
-
- The virgin bond behavior of all tested rebars was acceptable
  - All virgin rebars outperformed the $\geq 1.1\,\text{ksi}$ criteria by more than 200 %
- Rebars exposed to 4 and 7 pH environments continued to outperformed the requirement
- The surface enhancement of rebars exposed to 13 pH completely degraded

Summary of Research Conclusions

Prediction Model

- A prediction model was developed to define C_E based on exposure type
- Long-term strength retention of BFRP was calculated using the model
- Model validation
  - Through literature data (GFRP bars)
- Sufficient data was not available from this project to fully validate the model for BFRP bars
- Additional research needed to better predict service-life

Further Recommendations

Further Recommendations

- FRP rebars are considered a preferable alternative in harsh environments
- Caution!
- Specifically in harsh environments, rebars may degrade
  - Highly dependent on actual/specific product
- Require or verify durability data before usage in (extremely) harsh environments

Further Research Needs

Further Research Needs

- Accelerated aging usually done in aqueous solutions
  - Aqueous solutions may not simulate concrete environment properly

- Conduct study to correlate the aqueous solutions to real concrete environment
  - Rebar saturated with high pH and high salinity
  - Rebar saturated with salinity and exposed to high pH at the surface and

Further Research Needs

- Expose real concrete elements reinforced with BFRP rebars
  - To combined environment (> 13 pH $+$ high salinity)
- Use study to further improve the environmental reduction factor (C_E)

Further Research Needs

- Limited research on flexural, shear, and cracking behavior of beams reinforced with BFRP
  - Conduct testing on BFRP concrete elements

- The bond reduction factor (C_b) is determined based on flexural testing
  - Include concrete beam flexural tests in follow up study

Closing Remarks

Closing Remarks

Acknowledgment

- Steven Nolan
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- FDOT Administration

- Research Assistants
- Support Students

Closing Remarks

Questions?

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