DURABILITY OF GFRP REINFORCEMENT IN SEACON

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ABSTRACT

This paper presents partial results of an international collaborative project named 'SEACON' that aims at demonstrating the safe and durable utilization of seawater and salt-contaminated aggregates (natural or recycled) for a sustainable concrete production when combined with noncorrosive reinforcement. Seawater and salt-contaminated aggregates use in reinforced concrete (RC) is currently prohibited by building codes due to corrosion of the steel reinforcement. To this end, the concrete made with seawater and salt-contaminated aggregate is combined with noncorrosive reinforcement (i.e. Glass-Fiber-Reinforced-Polymer (GFRP) or stainless steel). The initial results presented herein evaluate the durability of GFRP bars embedded in concrete with no chloride limit. RC specimens were immersed in seawater at 60°C as accelerated conditioning. The residual mechanical properties of the embedded GFRP bars, which first established on pristine companion samples prior to casting (i.e. tensile strength, chord modulus of elasticity, transverse and horizontal shear strength), were evaluated after six months exposure to accelerated conditioning. The experimental results indicate no substantial degradation of GFRP bars embedded in concrete with no chloride limit exposed to accelerated conditioning for six months.

1. INTRODUCTION

The SEACON project aims at demonstrating the safe utilization of seawater and salt contaminated aggregates (natural or recycled) for a sustainable concrete production when combined with noncorrosive reinforcement to construct durable and economical concrete infrastructures [1]. Evidently, due to the high chloride content of seawater and salt-contaminated aggregates, its use in reinforced concrete (RC) is prohibited by building codes due to corrosion of the steel reinforcement. Redefining sustainable concrete with SEACON requires the use of alternative noncorrosive reinforcement material technologies, such as Glass-Fiber-Reinforced-Polymer (GFRP) or stainless steel. Preliminary results of the durability of the concrete without chloride limit have been published in other papers by the SEACON research team [1-5]. These studies have shown that chloride has no significant impact on the durability of concrete if the corrosion issue is addressed by replacing steel with noncorrosive reinforcement. It was shown that compressive and splitting tensile strength of the concrete made with sweater and salt contaminated recycled aggregate is comparable with conventional concrete after one-year exposure to different environmental conditions (i.e., subtropical environment in Coral Gables, FL, tidal zone in Key

Biscayne, FL, and immersion in seawater). The current study aims at assessing the durability of GFRP bars used as internal reinforcement of concrete made with seawater. The durability of stainless steel in RC structures with mixed-in seawater has also been studied by Lollini and coworkers [2]. Accelerated conditioning with the acceleration factor of elevated temperature is being used. The Arrhenius model will be used to correlate the data from accelerated conditioning to long-term durability of GFRP bars.

Several studies were conducted on durability of GFRP reinforcement in concrete structures. Most of them aged the bars in simulated concrete pore-solutions but few studies were performed on GFRP bars embedded in concrete environment, which simulates actual application conditions. Among those few studies, only a couple assessed the combined effect of saline solution and alkaline environment of the actual concrete on the durability of GFRP reinforcement. Since, the degradation rate of GFRP bars mainly depends on diffusion rate and chemical reaction rate and both of which can be accelerated by elevated temperatures, in most of the durability tests, elevated temperatures are used to accelerate the attack of simulated environments on FRP bars.

Robert and Benmokrane [6] immersed mortar-wrapped GFRP bars in 3% NaCl solution at 23, 40, 50, and 70°C for 365 days. The bars were extracted from mortar and tested in terms of tensile properties and microstructural degradation as a measure of the durability performance. It was shown that the combination of alkali environment of concrete and saline solution has no significant effect on the durability of GFRP reinforcement even at high temperatures. Residual strength of two types of GFRP bars embedded in seawater-contaminated concrete was examined by El-Maaddawy et al. [7]. GFRP-reinforced concrete prisms were conditioned in tap water tanks with the temperature of 20, 40, and 60°C for 450 days. Test results showed different performance for two types of GFRP bars. The tensile strength reduction was in the range of 2 to 15% for the GFRP bar Type I, and 19 to 50% for GFRP bar Type II. It was concluded that durability of the GFRP reinforcement is highly dependent on manufacturing, chemical composition of the resin matrix, characteristics of the interface, and interfacial imperfections that may develop during the manufacturing process.

The current study is aimed to evaluate the durability of GFRP reinforcement with an approach closer to field conditions. GFRP bars were embedded in concrete beams and immersed in seawater at 60°C. The total length of the conditioning will be two years. In order to monitor performance, GFRP bars are being extracted and tested in terms of physical, mechanical, and microstructural properties every six months. This study is part of an ongoing durability research program and this paper only covers the residual mechanical properties of the extracted GFRP bars (i.e. tensile properties, interlaminar shear and transverse shear strength) after six months exposure to accelerated conditioning.

2. EXPERIMENTAL METHOD

2.1 Concrete Mixtures

Reinforced concrete specimens from two different mixtures were cast: the first one, designated **Mix A**, is the reference conventional concrete. **Mix B** is the mix where the influence of seawater is assessed. Its mix proportion is identical to Mix A, but fresh water is substituted with seawater from Key Biscayne Bay (Florida). Table 1 shows the mix proportions.

Table 1 Mixture Proportions

Materials	**Units**	**Mix A**	**Mix B**
Portland Cement I-II (MH) low alkali	kg/m^3	332	
Fly ash (class F) per ASTM C618		83	
Tap water		168	-
Seawater		-	168
Coarse aggregate (#57 stone)		1038	
Fine aggregate (silica sand)		612	
Set retarding (BASF 961r)	mL/m^3	830	
Air-entraining (BASF AE90)		310	
Water-binder (w/b) ratio		0.4	

2.2 Characterization of Raw Materials

Concrete: A type II cement meeting the requirements of ASTM C 150 and type F fly ash per ASTM C 618 was used in this study. Tap water and seawater from Key Biscayne Bay (FL) were used as mixing water. Chemical composition of the tap water and seawater used in concrete mixtures can be seen in Table 2. Miami oolite with a nominal maximum aggregate size of 1" was used as the course aggregate and silica sand as the fine aggregate.

Table 2 Chemical composition of tap water and seawater used in concrete mixtures

Element		**Units**	**Tap water**	**Seawater**
Calcium	Ca	ppm	90	389
Chloride	Cl	ppm	44	18,759
Iron	Fe	ppm	-	0.5121
Potassium	K	ppm	6	329
Magnesium	Mg	ppm	6	1,323
Sodium	Na	ppm	26	9,585
Sulfate	SO_4^{2-}	ppm	8	831
Nitrate	NO_3	ppm	1	0.1345
Salinity		ppt	<0.5	35

GFRP: the bars were made of boron-free ECR glass fibers embedded in a vinyl ester resin. The mechanical and physical properties of 15.8 mm diameter unaged GFRP bars, serving as the benchmark, were examined per ASTM standards and summarized in Table 3.

Table 3 Physical and Mechanical Properties of the Pristine Bars

Material Property		**Test Standard**	**Unit**	**Value**
Physical	Cross-sectional area	ASTM D792	mm^2	221
	Fiber content	ASTM D2584	% volume	76
	Moisture absorption	ASTM D570	%	23
Mechanical	Tensile strength	ASTM D7205	MPa	1132
	Tensile chord modulus of Elasticity	ASTM D7205	GPa	53
	Transverse shear strength	ASTM D7617	MPa	181
	Horizontal shear strength	ASTM D4475	MPa	36

2.4 Characterization of Fresh and Hardened Concrete

Slump, density and air content of the fresh concrete were measured per ASTM C143, ASTM C138, and ASTM C231, respectively. Plain concrete cylinders with the dimension of 100x200 mm were cast to obtain compressive strength values at 3, 7, and 28 days of moist curing (100% relative humidity and temperature of 25°C) and 6 months, 1, 1.5, and 2 years of exposure to seawater at 60^{o}C as the accelerated conditioning and moist curing as control environment. These results provide an indication of the performance of the concrete surrounding the GFRP bars. In this paper, only the results for 6 months exposure are presented. Figure 1 (a) and (b) show the concrete cylinders in moist curing room as the control environment and chambers with seawater at 60°C as accelerated condition, respectively.

(a) (b)

Figure 1: Exposure conditions (a) Control environment: moist curing room (b) Accelerated condition: seawater at 60 °C

2.5 Durability of the GFRP bars

GFRP bars were embedded in concrete beams made from the two mixtures with the dimension of 150x190x1420 mm that leads to a minimum of 30 mm concrete cover. Each specimen was reinforced with four #5 GFRP bars, 1360 mm long, and immersed in seawater at 60° C as accelerated conditioning. This environment increases the diffusion rate of the concrete pore solution into the GFRP bars and accelerates the degradation chemicals reactions for the same time of immersion. Every six months one beam is removed from hot seawater chamber and the bars are extracted from the concrete and tested in terms of residual tensile properties and transverse and horizontal shear strength as an indicator of degradation due to exposure. All these properties are critical for application of GFRP bars as reinforcement in concrete structures and useful test methods for quality control. This paper covers the performance of GFRP bars aged for 6 months with accelerated conditioning. Test beams and seawater chambers at elevated temperature (60°C) for accelerated conditioning are shown in Figure 2 (a) and (b), respectively.

(a) (b)

Figure 2: (a) Test beams (b) Seawater chambers for accelerated conditioning

Tensile Properties: The ultimate tensile strength and chord modulus of extracted GFRP bars after 6 months exposure to the combination of concrete environment and accelerated condition were examined per ASTM D7205. Steel-pipe anchors were used and each specimen was instrumented with a linear variable differential transformer (LVDT) to capture the elongation during testing. The test was carried out using a Baldwin testing machine. Figure 3(a) shows the test set up.

Interlaminar-shear Strength: The horizontal shear strength of the extracted GFRP bars was determined per ASTM D4475 (2016). Specimens were tested with the span to diameter ratio equal to five, leading to 82.5 mm long GFRP segments center-loaded as shown in Figure 3(b). The ends of the specimens rest on two supports that allow the specimen to bend. The load being applied at a rate of crosshead motion of 1.3 mm /min. The specimen is deflected until a shear failure occurs at the midplane of the horizontally supported rod.

Transverse Shear Strength: extracted GFRP bars were cut in 9 inches segments and fitted into a double shear fixture with appropriate cutting blades and clamped into place per ASTM D7617. The shear fixture is mounted into a Universal mechanical testing machine and loaded to failure while recording force and crosshead displacement. The test setup is shown in Figure 3(c).

(a) (b) (c)

Figure 3: Test setups for measuring (a) Tensile properties (b) Interlaminar shear strength (c) Transverse shear strength

3. PRELIMINARY RESULTS

3.1 Fresh Concrete Properties

The fresh concrete properties shown in Table 4 has not been effected by introducing seawater to the mixture, however, the setting time decreased significantly due to the high chloride content of the seawater. Chemical admixtures can be used to control the accelerating effect of chloride.

Table 4: Fresh Concrete Properties

Mixture type	Slump		Density		Air Content (%)	Concrete temperature	
	in.	mm	lb./ft^3	kg/m^3		°F	°C
Mix A	4	100	146.8	2349.9	1.3	80	26
Mix B	3.75	95	147.2	2358.6	1	80	26

3.2 Compressive Strength

Preliminary results after 6 months exposure to control and accelerated conditioning are shown in Figure 4. Solid lines show strength of specimens exposed to control conditioning, however dashed lines are representing specimens exposed to accelerated conditioning. As shown in Figure 4 replacing fresh water with seawater in mixing concrete has no significant effect on compressive strength of concrete even after six months exposure to accelerated conditioning. Seawater concrete showed higher compressive strength in early ages, which is in agreement with the literature due to accelerating effect of chloride, present in the seawater.

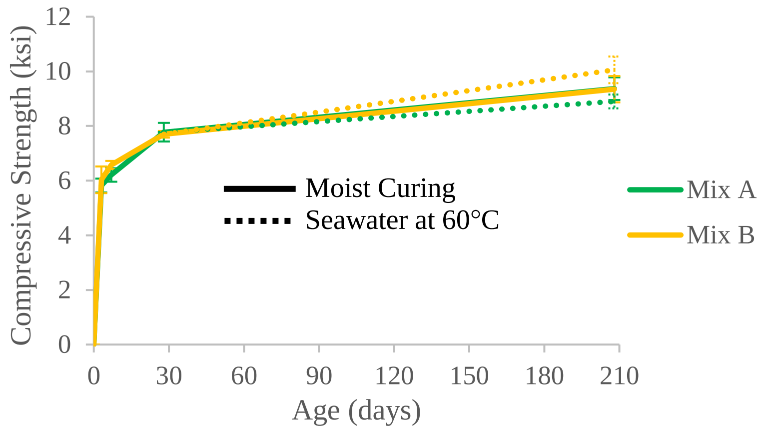

Figure 4: Compressive strength after 6 months exposure to control and accelerated conditioning

3.3 Durability of the GFRP bars

Tensile properties: Specimens failed through the rupture of fibers. The failure was accompanied by the delamination of fibers and resin, as shown in Figure 5(a). Table 5 shows the tensile strength and chord modulus of the extracted GFRP bars after six months exposure to the combination of concrete environment and accelerated condition. The tensile strength and chord modulus of the GFRP bars embedded in both conventional and seawater concrete slightly increased over 6 months in accelerated condition. This could be related to resin crosslinking over time due to elevated temperature.

Interlaminar Shear Strength: GFRP specimens in short beam test failed in shear mode (horizontal cracks along the mid-plane of the specimens) as shown in Figure 5 (b). The experimental results obtained from the horizontal shear tests on the extracted bars after 6 months immersion in seawater at 60°C is shown in Table 5. Likewise tensile properties, the horizontal shear strength of the GFRP bars embedded in seawater concrete increased over 6 months exposure to the combination of concrete environment and accelerated conditioning. However, the bars embedded in conventional concrete lost 5% of their horizontal shear strength. These preliminary results will be completed every 6 months for 2 years, which makes it easier to comment on the horizontal shear performance of embedded GFRP bars.

Transverse Shear Strength: The failure mode of the extracted GFRP bars is shown in Figure 5 (c). It can be seen in Table 5 that the transverse shear strength of the embedded GFRP bars slightly decreases over 6 months immersion in seawater at 60° C which is expected due to exposure to high temperature. However, the performance of embedded GFRP bars in conventional and seawater concrete is comparable which means the introduction of seawater into concrete as mixing water has no significant effect on the durability of GFRP bars. As mentioned before, additional testing will be performed to confirm these results.

(a) (b) (c)

Figure 5: Typical failure mode of the extracted GFRP bars subjected to (a) Tensile test (b) Interlaminar shear test (c) Transverse shear test

Table 5 Mechanical properties of the extracted GFRP bars in comparison with pristine bars

Mechanical Properties	Pristine bars (CV%)	Extracted bars (CV%)	
		Mix A	Mix B
Tensile strength (MPa)	1132 (2.2)	1172 (2.1)	1173 (0.1)
Tensile chord modulus of Elasticity (GPa)	53 (3.5)	57 (1.1)	57 (2.5)
Horizontal shear strength (MPa)	36 (3)	34 (4.2)	37 (9.2)
Transverse shear strength (MPa)	181 (5.2)	172 (3.5)	159 (4.9)

4. CONCLUSIONS

Seawater concrete has shown comparable performance in terms of compressive strength to conventional concrete after 6 months immersion in seawater at 60° C as accelerated condition. This means that the concrete mixtures, which are surrounding the GFRP bars, have the same mechanical properties. The results presented in this paper clearly illustrates that tensile properties of the bars embedded in both conventional and seawater concrete slightly improved after 6 months exposure to accelerated conditioning. The shear performance of the bars embedded in conventional concrete decreased over time. However, it can be seen that the combination of seawater concrete and accelerated conditioning has a positive impact on the horizontal shear strength of the embedded GFRP bars and negative impact on transverse shear strength. This study is part of an ongoing durability research program on GFRP reinforcement for concrete structures. Thus, more research will be conducted to confirm these results.

5. ACKNOWLEDGMENTS

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