DURABILITY OF GFRP REINFORCEMENT IN SEAWATER CONCRETE – PART I

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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. In response to this challenge, 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 (i.e., tensile strength, chord modulus of elasticity, transverse and horizontal shear strength) of the embedded GFRP bars, compared to pristine companion samples tested prior to casting, were evaluated after one-year exposure to accelerated conditioning. The experimental results show that the performance of the GFRP bars embedded in concrete with no chloride limit exposed to accelerated conditioning for one year is at least comparable to pristine rebars.

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].

Monitoring the performance of existing RC structures would give a real indication of the long-term durability of GFRP reinforcement; however, there has been only a few studies of this type due to the time issue and high cost [6-9]. Gooranorimi [6] extracted concrete cores with GFRP bars from a bridge which has been in service for 15 years. Scanning Electron Microscopy (SEM) imaging and Energy Dispersive X-ray Spectroscopy (EDS) were performed on GFRP coupons. Horizontal shear strength, glass transition temperature (T_g), and fiber content were measured and compared with the pristine bars at the time of construction. SEM and EDS showed no significant change in either GFRP microstructural or chemical composition. T_g and fiber content of the extracted rebars were comparable to pristine values while the results of the horizontal shear strength were inconclusive. A field study conducted by the Intelligent Sensing for Innovative Structures (ISIS) Canada Research Network collected data with respect to the durability of GFRP bars in concrete exposed to natural environments [8]. Concrete cores containing GFRP bars were extracted from five selected structures, a 5-year-old harbor wharf and four 6- to 8-year-old RC bridges. The GFRP bars were analyzed for their physical properties and chemical composition at the microscopic level. The experimental results were compared with the ones obtained from control GFRP bars preserved under controlled laboratory conditions. The results of the analyses showed that there is no degradation of the GFRP bars in the real-life concrete structures. The analyses also indicated that no alkali ingress was observed in the GFRP bars from the concrete pore solution. The resin matrix in all GFRP bars was intact and unaltered from its original state, neither hydrolysis nor significant changes in T_g took place after exposure for 5 to 8 years to the combined effects of the alkaline environment in the concrete and the external natural environment.

In order to save time and cost, several studies have used accelerated conditioning with the acceleration factor of elevated temperature to examine 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 [10] 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. [11]. 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 which is in agreement with other literatures [12, 13].

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. The Arrhenius model will be used to correlate the data from accelerated conditioning to long-term durability of the GFRP bars. 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 one-year exposure to accelerated conditioning. The results of six-months exposure was reported in earlier publication by the author[14].

2. EXPERIMENTATION

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		332	
Fly ash (class F) per ASTM C618		83	
Tap water	kg/m^3	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

<u>Concrete:</u> 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. Significant difference in the concentration of some chemical elements (i.e. Chloride, Potassium, Magnesium, Sodium, Sulfate, etc.) might cause some issues in the durability of concrete and GFRP reinforcement, which will be addressed in SEACON project. Miami oolite

with a nominal maximum aggregate size of 2.5 cm 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 E-CR glass fibers embedded in a vinyl ester resin. The mechanical and physical properties of 15.8 mm diameter (#5) 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 100 x 200 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 and 12 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 conditioning, respectively.

(a) (b)

Figure 1. Exposure conditions (a) Control environment: moist curing room (b) Accelerated conditioning environment: 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 150 x 190 x 1420 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 and 12 months in 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 and 12 months exposure to the combination of concrete environment and accelerated conditioning 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. 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 mid-plane of the horizontally supported rod.

Transverse Shear Strength: extracted GFRP bars were cut in 228 mm 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 (°C)**
	mm	**kg/m^3**		
Mix A (Conventional Concrete)	100	2349.9	1.3	26
Mix B (Seawater Concrete)	95	2358.6	1	26

3.2 Compressive Strength

Preliminary results after 6 and 12 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 the compressive strength of concrete even after one year of curing in the moist room. Seawater concrete showed higher compressive strength in early ages due to accelerating effect of chloride present in the seawater, and comparable long-term strength which is in agreement with the literature. It also showed better performance in accelerated conditioning. Six-months' results showed strength gain for both seawater and conventional concrete, however, slight decrease was observed after one-year exposure to accelerated conditioning. More compressive strength specimens will be tested every six months to better understand the behavior of the surrounding concrete.

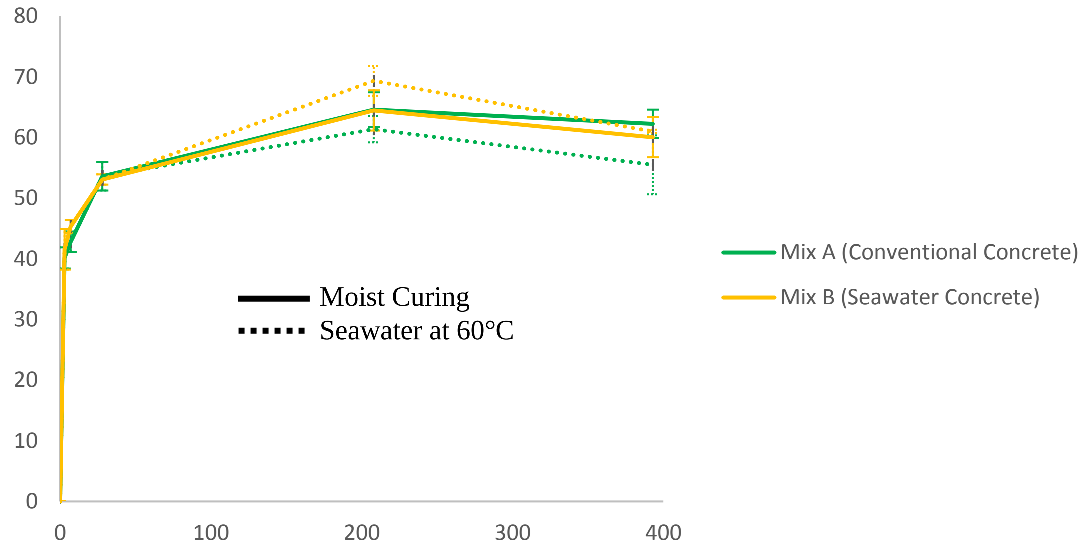

Figure 4. Compressive strength after one-year exposure to control and accelerated conditioning

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 residual tensile strength and chord modulus of the extracted GFRP bars after 6 and 12 months exposure to the combination of concrete environment and accelerated conditioning. The tensile strength and chord modulus of the GFRP bars embedded in both conventional and seawater concrete slightly increased over the first six months. This could be related to resin crosslinking in early ages due to elevated temperature. Despite the lower tensile strength and chord modulus after one-year exposure to accelerated conditioning, comparable performance was noticed between extracted GFRP bars from both conventional and seawater concrete. This shows that using seawater as mixing water has no significant effect on the durability of GFRP bars. These results will be updated every six months and will be used to predict the long-term performance of the GFRP reinforcement in seawater concrete.

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 and 12 months immersion in seawater at 60 °C are shown in Table 5. Likewise tensile properties, the horizontal shear strength of the GFRP bars embedded in seawater concrete increased over the first six-months exposure to the accelerated conditioning. However, the bars embedded in conventional concrete lost 5 % of their horizontal shear strength. The same trend of the better performance of the bars embedded in seawater concrete was observed even after one year by only 10 % decrease in interlaminar shear strength compared to 16 % for the bars extracted from conventional concrete. These preliminary results will be completed every six months for two years, which makes it easier to comment on the horizontal shear performance of the embedded GFRP bars and predict their long-term durability.

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 decreases over one year immersion in seawater at 60 °C which is expected due to exposure to high temperature. Better performance was recorded for GFRP bars extracted from conventional concrete after six months. However, bars embedded in seawater concrete had less degradation over the next six months with only 2 % decrease in transverse shear strength compared to 23 % for the conventional concrete GFRP reinforcement. 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%)	6 months (CV%)		1 year (CV%)	
		Mix A	Mix B	Mix A	Mix B
Tensile strength (MPa)	1132 (2.2)	1172 (1.2)	1173 (0.1)	1117 (0.1)	1095 (3.7)
Tensile chord modulus of Elasticity (GPa)	52.72 (3.5)	57.25 (1.1)	56.56 (2.5)	50.91 (0.2)	51.13 (0.7)
Horizontal shear strength (MPa)	35.53 (3)	33.44 (4.2)	37.09 (9.2)	29.82 (4.2)	32.10 (6.6)
Transverse shear strength (MPa)	181 (5.2)	172.25 (3.5)	158.45 (4.9)	139.15 (11.8)	154.82 (4.1)

4. CONCLUSIONS

Seawater concrete has shown comparable and even better performance in terms of compressive strength compared to conventional concrete after one-year curing in moist room and seawater at 60 °C as accelerated conditioning environment, respectively. This means that the two concrete matrices surrounding the GFRP bars have almost the same mechanical properties. Tensile properties of the bars embedded in both conventional and seawater concrete are comparable after one-year exposure to accelerated conditioning. Seawater concrete appears to have a positive impact on the horizontal and transverse shear strength of the embedded GFRP bars. The results presented in this paper clearly illustrate the better or at least comparable performance of the GFRP bars extracted from seawater concrete in comparison to conventional concrete after one-year exposure to accelerated conditioning. Thus, introducing seawater into the mixture, as the mixing water has no significant effect on the durability of GFRP bars.

This study is part of an ongoing durability research program on GFRP reinforcement for concrete structures. Additional research will be conducted to confirm these results with the aim of predicting the long-term durability of the GFRP reinforcement in seawater concrete.

5. ACKNOWLEDGMENTS

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