



SEACON

Sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement

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1 INTRODUCTION

This report presents the partial results of WP2 of the SEACON project which relate to the long-term durability of GFRP bars embedded in concrete with no chloride limit. GFRP-reinforced concrete specimens were immersed in seawater at 60 °C which is an accelerated conditioning environment. The residual mechanical properties (i.e., tensile strength, chord modulus of elasticity, and 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.

In addition to the lab-scale experiments, two demo projects (one in Piacenza, Italy and one in Florida, USA) are being performed as WP4 of the SEACON project, addressing two different infrastructure elements at locations with very different (micro) climates (i.e., a continental one, away from the coastline, and a subtropical one, along the coastline). The Florida demo project is a 57 m long vehicular bridge which features sustainable concrete using seawater and recycled salt contaminated aggregates in its bulkhead caps and gravity walls, respectively. All these elements will be reinforced with GFRP bars. Furthermore, GFRP will be used in other structural elements such as pile caps, deck and traffic railings. The latter will be cast with a concrete mix made of white cement as the binder (one bridge side) and high volume slag (other bridge side). Provisions have been made for casting test blocks from the bulkhead caps, gravity walls, and traffic railings in order to extract reinforcing bars from them thus allowing monitoring of their performance over time and verification of the lab-scale results.

Monitoring the performance of existing RC structures would give an accurate indication of the long-term durability of GFRP reinforcement; however, there have been only a few studies of this type due to time and cost considerations [1-4]. Gooranorimi [1] 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 values obtained from 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 to determine the durability of GFRP bars in concrete exposed to natural environments [3]. 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 real-life concrete structures for that time of exposure. 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 due 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 being elevated temperature in order to examine durability of GFRP reinforcement in concrete structures [5 – 12]. Since the degradation rate of GFRP bars mainly depends on the diffusion rate and the chemical reaction rate, both of which can be accelerated by elevated temperatures, elevated temperatures are used in most of the durability tests to accelerate the attack of simulated environments on GFRP bars. Most studies aged the bars in simulated concrete pore-solutions [5 – 9], but few investigations were performed on GFRP bars embedded in concrete

environment, which simulates actual application conditions [10 – 12]. Among the latter studies, only a couple assessed the combined effect of saline solution and alkaline environment of the actual concrete on the durability of GFRP reinforcement [11 – 12].

Robert and Benmokrane [11] immersed mortar-wrapped GFRP bars in 3% NaCl solution at 23, 40, 50, and 70 °C for 365 days. The bars were extracted from the mortar and tested in terms of tensile properties and microstructural degradation as a measure of durability performance. It was shown that the combination of the alkali environment of concrete and the saline solution had 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. [12]. 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 the two selected 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. In agreement with other technical literature [13, 14], it was concluded that durability of the GFRP reinforcement is highly dependent on manufacturing, chemical composition of the resin matrix, characteristics of the fiber-resin interface, and interfacial imperfections that may develop during the manufacturing process.

This current WP2-SEACON study is aimed at evaluating the durability of GFRP reinforcement under conditions closer to field conditions. GFRP bars were embedded in concrete elements and immersed in seawater at 60 °C. The total duration of the conditioning time will be two years. In order to monitor performance, GFRP bars are being extracted and tested in terms of mechanical properties every six months [15]. The Arrhenius model will be used to correlate the data from accelerated conditioning to long-term durability of the GFRP bars. This report covers the residual mechanical properties of the extracted GFRP bars (i.e., tensile properties, and interlaminar and transverse shear strengths) after one-year exposure to accelerated conditioning. Similarly, test blocks from different elements of the Florida field demo (the Halls River Bridge) will be cast and GFRP bars extracted from them in order to monitor their performance and validate the lab-scale results.

2 EXPERIMENTATION

2.1 Concrete Mixtures

Reinforced concrete specimens from two different mixtures were cast: **Mix A** is the reference conventional concrete, and **Mix B** is the one 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

Material	Units	Mix A	Mix B
Portland cement I-II (MH) low alkali	kg/m ³	332	
Fly ash		83	
Tap water		168	-
Seawater		-	168
Coarse aggregate		1038	
Fine aggregate		612	
Set retarding admixture (MasterSet R 961)	ml/m ³	830	
Air-entraining admixture (MasterAir AE 90)		310	

2.2 Characterization of Raw Materials

Concrete: A type II cement meeting the requirements of ASTM C 150 and a type F fly ash conforming to ASTM C 618 were used in this study. Tap water and seawater from Key Biscayne Bay (FL) were used as mixing water, respectively, with chemical composition as shown in

Table 2. One of the objectives of this study is to determine if the high concentration of some chemical ions (i.e., chloride, potassium, magnesium, sodium, sulfate, etc.) in the seawater might result in a reduced durability of the concrete and GFRP reinforcement.

Miami oolite with a nominal maximum aggregate size of 25 mm was used as the coarse aggregate and silica sand as the fine aggregate.

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

Ions	Units	Tap Water	Seawater
Calcium	ppm	90	389
Chloride	ppm	44	18,759
Iron	ppm	-	0.512
Potassium	ppm	6	329
Magnesium	ppm	6	1,323
Sodium	ppm	26	9,585
Sulfate	ppm	8	831
Nitrate	ppm	1	0.134

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. Five repetitions were performed for each test and the coefficient of variance for the collected data is also provided in Table 3.

Table 3 Physical and mechanical properties of the pristine bars

Material Property		ASTM Standard	Unit	Value	CV%
Physical	Cross-sectional area	D792	mm ²	220.89	0.66
	Fiber content	D2584	% vol.	76.15	0.82
	Moisture absorption	D570	%	23	5.9
Mechanical	Tensile strength	D7205	MPa	1,132	2.2
	Tensile chord modulus of elasticity	D7205	GPa	52.72	3.5
	Transverse shear strength	D7617	MPa	181	5.2
	Horizontal shear strength	D4475	MPa	35.53	3.0

2.3 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 dimensions 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 °C as the accelerated conditioning environment and moist curing as control environment. These results provide an indication of the performance of the concrete surrounding the GFRP bars. In this report, only the results for six months and one-year 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.



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

2.4 Durability of GFRP Bars

GFRP bars were embedded in concrete elements made from the two mixtures with dimensions 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 chemical degradation processes for the same time of immersion. Every six months one element is removed from the 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. 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 six months and one year in accelerated conditioning. Test elements and seawater chambers at elevated temperature (60 °C) for accelerated conditioning are shown in Figure 2(a) and (b), respectively.

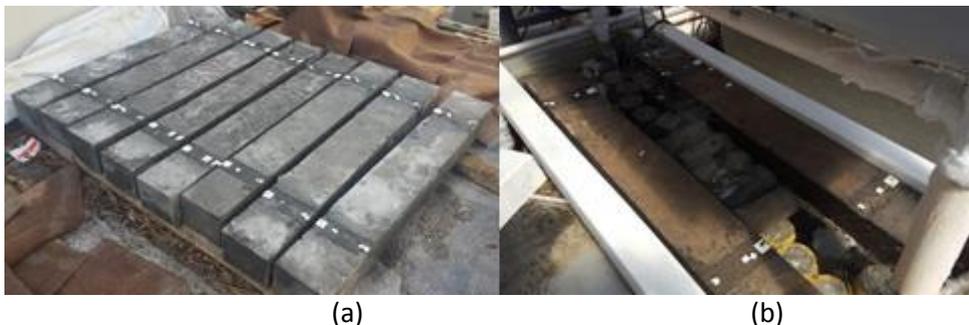


Figure 2 (a) Test elements; (b) Seawater chambers for accelerated conditioning

Tensile Properties: The ultimate tensile strength and chord modulus of extracted GFRP bars after six 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 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 specimen rest on two supports that allow the specimen to bend. The load was 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 bar.

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).

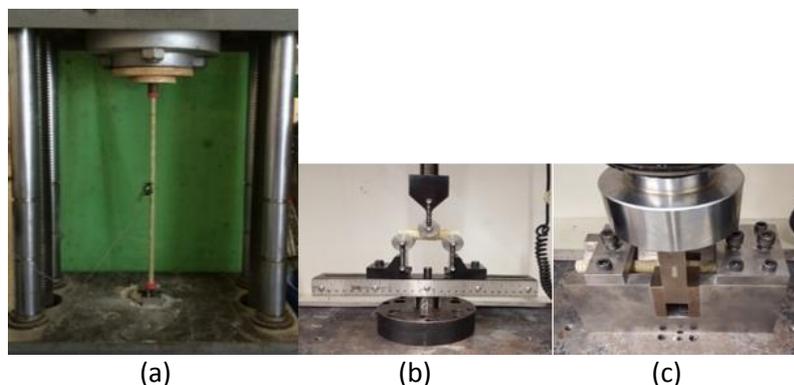


Figure 3 Test setups for measuring: (a) Tensile properties; (b) Interlaminar shear strength; (c) Transverse shear strength

3 PRELIMINARY EXPERIMENTAL RESULTS

3.1 Fresh Concrete Properties

The fresh concrete properties are shown in Table 4. These properties were not affected by introducing seawater to the mixture; however, the setting time decreased significantly due to the high chloride content of the seawater which was controlled by retarding admixtures. The temperature of the fresh concrete was measured at the time of casting specimens by thermometer.

Table 4 Fresh concrete properties

Mixture type	Slump (mm)	Density (kg/m ³)	Air Content (%)	Concrete Temperature (°C)
Mix A (Conventional Concrete)	100	2349.9	1.3	26
Mix B (Seawater Concrete)	95	2358.6	1.0	26

3.2 Compressive Strength

Preliminary results after six and 12 months exposure to control and accelerated conditioning are shown in Figure 4. Solid lines show strength of specimens exposed to control conditioning while dashed lines represent specimens exposed to accelerated conditioning. As shown in Figure 4, replacing fresh water with seawater 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 at early ages due to accelerating effect of chloride present in the seawater. Conversely, the two mixtures had comparable long-term strength in agreement with the literatures [16, 17].

Seawater concrete showed better performance in accelerated conditioning. Six-month 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 trends.

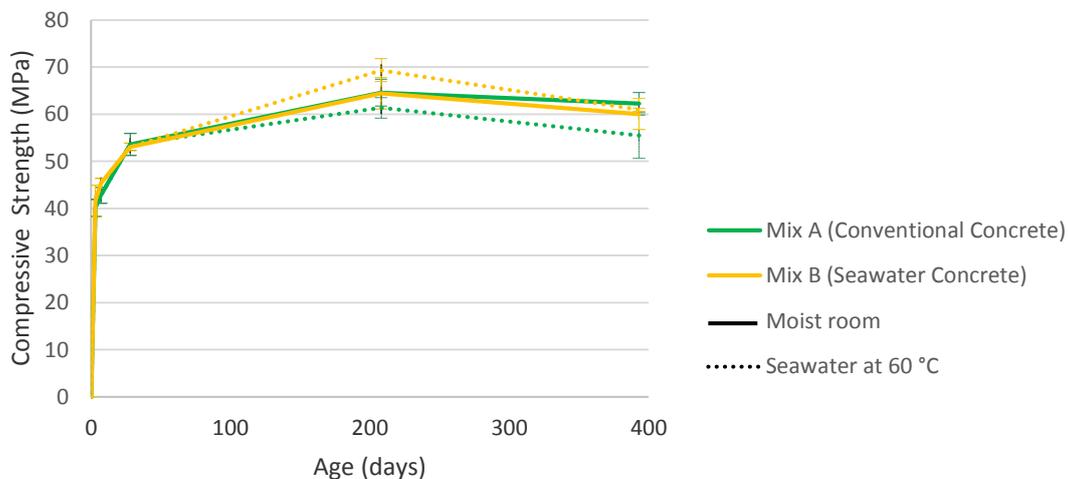


Figure 4 Compressive strength after one-year exposure to control and accelerated conditioning

3.3 Durability of GFRP Bars

Tensile properties: Specimens failed by 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 six 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 six and 12 months immersion in seawater at 60 °C are shown in Table 5. Similar to tensile properties, the horizontal shear strength of the GFRP bars embedded in seawater concrete increased over the first six-month exposure to the accelerated conditioning. However, the bars embedded in conventional concrete lost 5% of their horizontal shear strength. The same trend of better performance of the bars embedded in seawater concrete was observed even after one year with only a 10% decrease in interlaminar shear strength compared to 16% for the bars extracted from conventional concrete. These preliminary results will be updated every six months for two years, which making 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. Additional testing will be performed over time to confirm these results.

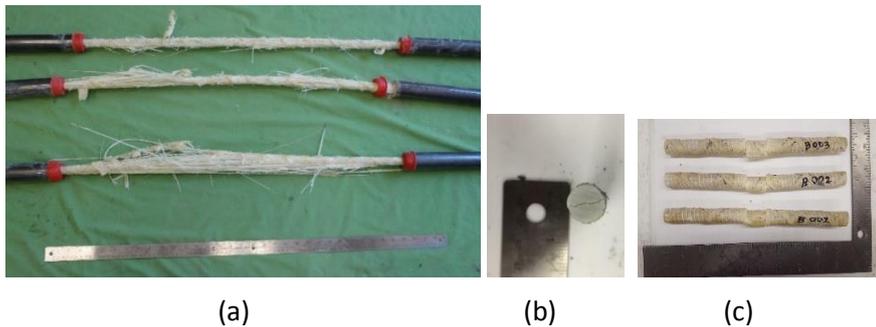


Figure 5 Typical failure mode of the extracted GFRP bars subjected to: (a) Tensile test; (b) Interlaminar shear test; (c) Transverse shear test

Table 5 Mechanical properties of pristine and extracted GFRP bars

Mechanical Property	Pristine (COV%*)	6-month (COV%)		1-year (COV%)	
		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 (3.0)	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)

*COV% = Coefficient of Variance

4 HALLS RIVER BRIDGE

4.1 Concrete Mixtures

Bulkhead caps will be cast with Green concrete which has identical mixture proportions to conventional concrete used in other elements of the bridge (Class IV) but fresh water replaced by seawater. A retarder will be used to offset the accelerating effect of seawater due to its high chloride content. Mixture design and fresh properties of the Green and conventional concrete are reported in Table 6 – 7. As it can be seen in Figure 6, seawater concrete (Green) has higher early age strength than conventional concrete.

Table 6 Mixture proportions of Green and conventional concretes

Material	Units	Conventional Concrete	Green Concrete
Portland Cement I-II (MH) low alkali	kg/m ³	208	
Slag		208	
Fresh water		158	-
Seawater		-	158
Coarse aggregate		997	
Fine aggregate		691	
Set retarding admixture (Recover)	ml/m ³	-	2179
Air-entraining admixture (MasterAir AE 90)		20	
Water reducing admixture		817	

Table 7 Fresh concrete properties

Mixture type	Slump (mm)	Density (kg/m ³)	Air content (%)	Concrete temperature (°C)
Conventional Concrete	100	2277.8	2.1	36.6
Green Concrete	82.5	2269.8	2.0	35.0

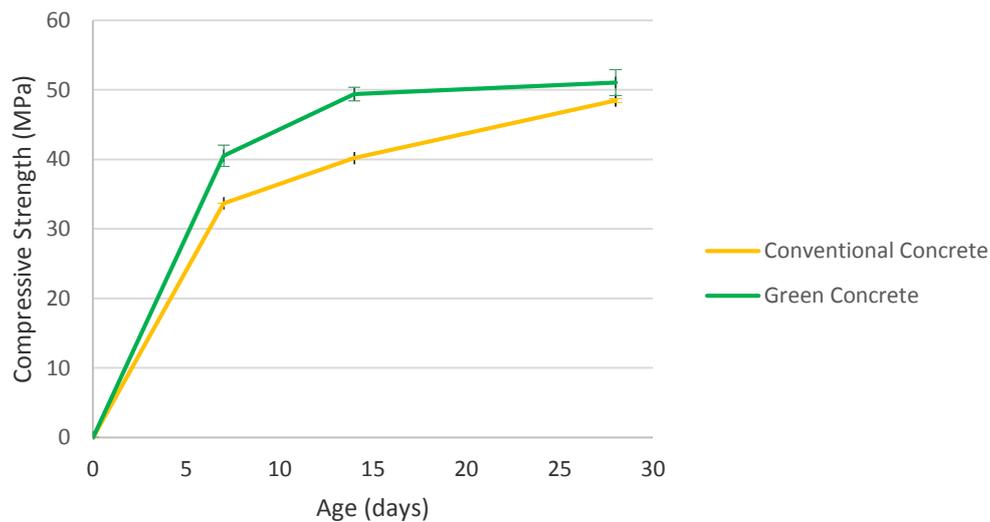


Figure 6 Early age compressive strength of Green and conventional concretes

RAP concrete in which Recycled Asphalt Pavement (RAP) partially replaces the total aggregate, will be used in a gravity wall of Halls River Bridge. Since RAP has a wide range of particle size with the nominal maximum aggregate size of 13 mm, it was treated as both coarse and fine aggregate. Specific gravities, water absorption, fine modulus, and -200 ratio of RAP is reported in Table 6. Recycled Concrete Aggregate (RCA), with the nominal maximum aggregate size of 1", will also be used as partial replacement for the coarse aggregate in a gravity wall. Different properties of the RCA were measured and are presented in Table 8. The mixture proportion, fresh and hardened properties of the RAP and RCA concrete are shown in Table 9 – 10, and Figure 7, respectively. Higher air content was measure for RAP concrete compared to RCA concrete, although the same amount of air entraining admixture was used for both mixtures. More research is needed to find what exactly is causing this difference.

Table 8 Properties of the RAP and RCA materials

Property	RAP	RCA
Absorption	2.23%	7.49%
Specific Gravity (SSD)	2.351	2.291
-200	0.15%	0.66%
Fineness modulus	5.34	-

Table 9 Mix proportions for RAP and RCA concretes

Material	Unit	RAP	RCA
Portland cement I-II (MH) low alkali	Kg/m ³	120	120
Slag		225	225
Coarse aggregate		615	776
Fine aggregate		828	833
RCA		-	191
RAP		341	-
Water		158	153
Set retarding admixture (Recover)		ml/m ³	902
Water reducing admixture	677		677
High range water reducing admixture (ADVA 140M)	902		902
Air-entraining admixture	7.7		7.7

Table 10 Fresh properties of RAP and RCA concretes

Mixture type	Slump (mm)	Density (kg/m ³)	Air content (%)	Concrete temperature (°C)
RAP Concrete	114	2212.0	4.8	26
RCA Concrete	190	2218.5	2.8	26

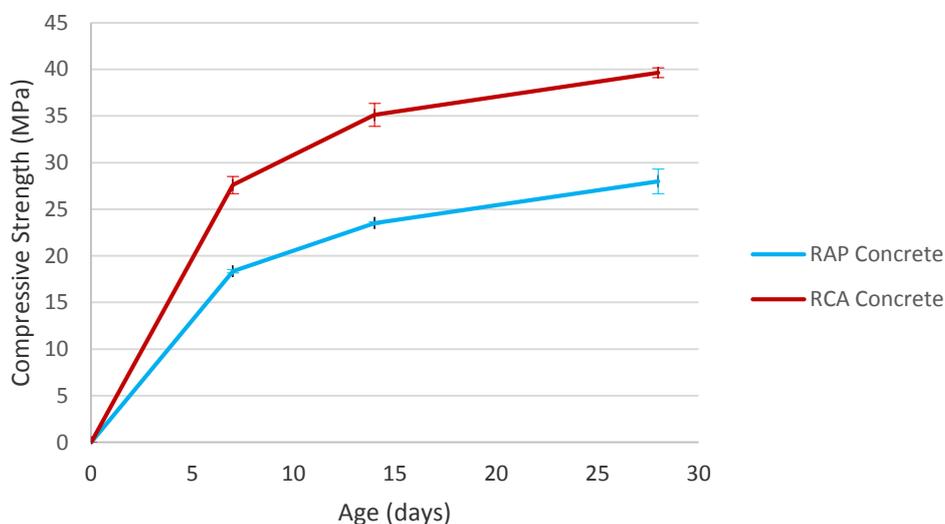


Figure 7 Early-age compressive strength of the RAP and RCA concretes

In order to increase the visibility, traffic railings will be cast with two concrete mixtures using 100% white cement and a blend of 60% slag and Portland cement. Their mixture proportions, fresh, and hardened concrete properties are shown in Table 11 – 12, and Figure 8, respectively.

Table 11 Mixture proportions of 60% slag and 100% white cement concretes

Materials	Unit	60% Slag	100% White Cement
Portland cement	Kg/m ³	166	-
White cement		-	418
Slag		249	-
Coarse aggregate		1015	1015
Fine aggregate		695	754
Water		163	147
Set retarding admixture (Recover)	ml/m ³	1650	1650
Water reducing admixture		825	825
Air-entraining admixture		20	20

Table 12 Fresh properties of 60% slag and 100% white cement concretes

Mixture type	Slump (mm)	Density (kg/m ³)	Air content (%)	Concrete temperature (°C)
60% slag concrete	95.0	2289.0	1.5	35
100% white cement concrete	63.5	2276.5	2.3	35

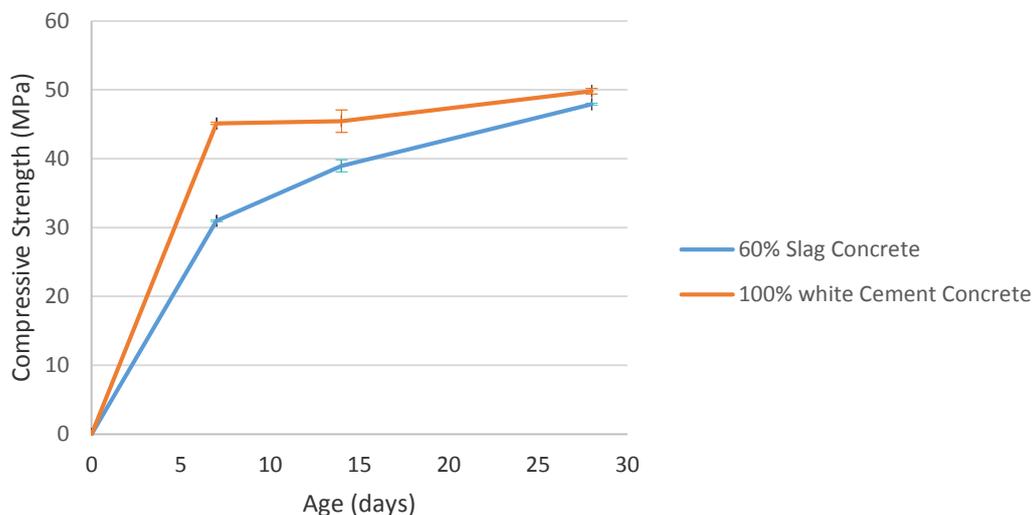


Figure 8 Early-age compressive strength of 60% slag and 100% white cement concretes

Higher early age strength but comparable 28 days compressive strengths were observed for Green and 60% slag concrete compared to conventional and 100% white cement concrete, respectively, which was expected. However, RCA concrete maintained its superior performance compared to RAP concrete even after 28 days. This was also expected due to the higher strength of RCA in comparison to RAP aggregate. Tia et al. [18] showed that RAP concrete has a lower modulus of elasticity than conventional concrete which may result in better crack control and load distribution in pavement slabs. The modulus of elasticity of RAP and RCA concrete will be measured for the batches used in the gravity walls.

4.2 Monitoring

Test blocks from different elements of the Halls River Bridge will be cast in order to monitor the performance and validate the lab results. Test blocks from the bulkhead cap are attached to the wall cap on the sea side. Seawater will be used as mixing water for these elements reinforced with three different types of composite bars made of glass, basalt and carbon fibers (i.e., GFRP, BFRP and CFRP). Test blocks will be extracted every six months to examine the state of both concrete and embedded FRP bars. Figure 9 shows the configuration of the bulkhead cap test blocks.

The test blocks from the RAP and RCA gravity walls will be cast separately at the time of the construction. Although gravity walls will be cast with conventional RAP and RCA concrete mixtures, half of the test blocks will be cast with Green RCA and RAP concrete which have identical mix design except the mixing water which is seawater. Similarly to the test blocks of the bulkhead cap, these test blocks will be reinforced with GFRP, BFRP, and CFRP providing the opportunity to monitor their performance when combining seawater and salt-contaminated recycled aggregates. The configuration of the gravity wall test blocks is shown in Figure 10.

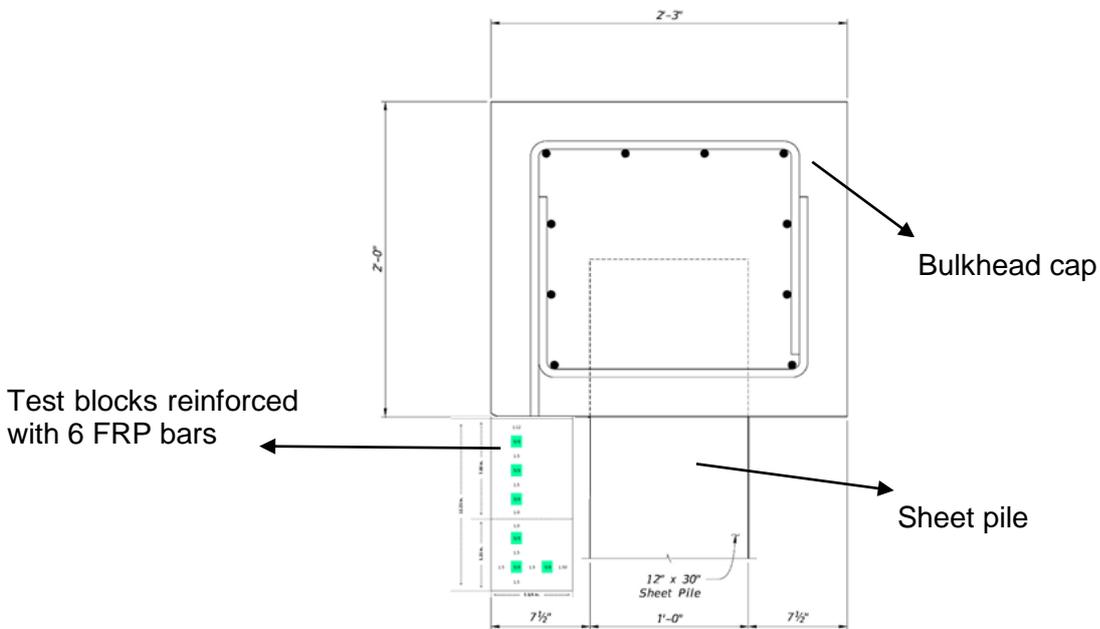


Figure 9 Configuration of the bulkhead cap test blocks (1 in = 25.4 mm)

Identical formwork will also be filled with the two concrete types used for the traffic railings made with white cement and a blend of slag and Portland cement, respectively. These test blocks will only be reinforced with GFRP bars.

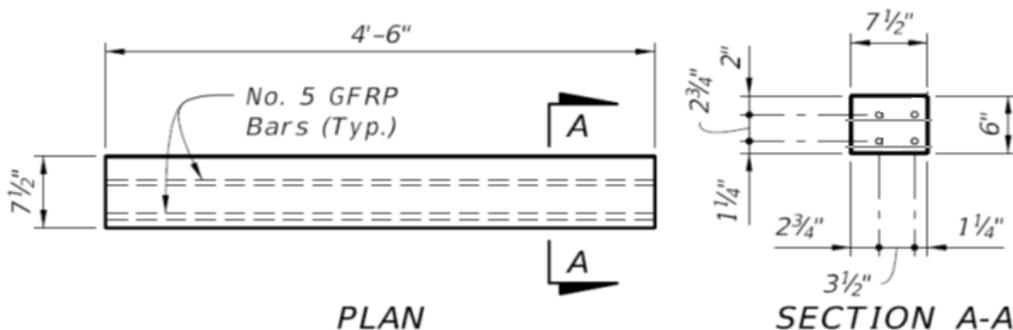


Figure 10 Configuration of the gravity wall test blocks (1 in. = 25.4 mm; 1 ft = 204.8 mm)

5 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 GFRP bars embedded in both conventional and seawater concretes are comparable after one-year exposure to accelerated conditioning. Seawater concrete appears to have a positive impact on the horizontal and transverse shear strengths of the embedded GFRP bars. The results presented in this report 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.

Based on one-year data, introducing seawater into concrete as the mixing water has no significant effect on the durability of GFRP bars. Additional research is planned to confirm these results with the aim of predicting the long-term durability of the GFRP reinforcement in both conventional and seawater concretes.

Test blocks from different concrete mixtures of the Halls River Bridge reinforced with composite bars made of GFRP, CFRP and BFRP will be collected and tested periodically in order to monitor materials performance and correlate the lab results with the ones obtained under field exposure.

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