Durability of Commercially Available GFRP Reinforcement in Seawater-Mixed Concrete under Accelerated Aging Conditions

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Abstract

The effect of seawater used as mixing water in concrete on the long-term properties of GFRP bars is the focus of this work. The durability of GFRP bars embedded in seawater-mixed concrete was studied in terms of residual mechanical properties (i.e. tensile strength, horizontal and transverse shear strength, and GFRP-concrete bond strength) after immersion in seawater at 60 °C for a period of 24 months. Benchmark specimens were also cast using conventional concrete. Results showed comparable performance in tensile and shear properties between the two sets of bars with some degradation of the mechanical properties in both cases. However, bond strength showed differences and the seawater-mixed concrete showed slightly lower bond performance over time.

SEM was used to identify degradation mechanisms. Areas with large concentrations of voids near the bar edge, formed during manufacturing, may provide a pathway for moisture and alkalis which could lead to the fiber disintegration and debonding between fibers and the resin. Over time, a greater number of fibers are affected, which leads to the formation of significant cracking near the edge. Results were qualitatively similar for embedded bars in seawater-mixed and conventional concrete, explaining the similar reduction in tensile properties, horizontal shear, and transverse shear strength seen in both sets of bars. However, the bond strength does not significantly decrease in these specimens over time for unclear reasons.

Key words: GFRP, durability, seawater, concrete, bond strength

Introduction

As fresh water is a finite resource, replacing fresh water with seawater for mixing concrete may be potentially advantageous, especially in regions such as the Middle East where fresh water may be scarce. Seawater-mixed concrete could also be a valuable repair material in reconstruction after natural disasters. Other similar solutions which lead to the conservation of resources are the use of beach sand to replace conventional concrete sand. However, mixing concrete using seawater (or beach sand) is prohibited in most building codes due to potential corrosion of the steel reinforcement (Ghorab et al. 1989). One solution is the use of non-ferrous, non-corrosive reinforcement such as Glass Fiber Reinforced Polymer (GFRP). GFRP has shown promise as a replacement for steel in chloride-rich environments, such as marine structures, due to its non-corrosive nature (Nanni et al. 2014). The current study aims to assess the long-term durability of GFRP bars in seawater-mixed concrete using accelerated aging as there are no existing seawater-mixed concrete structures reinforced with GFRP bars. Longer-term testing on field structures and using conventional aging methods is ongoing, but this is out of the scope of this work.

Long-term performance of GFRP reinforcement in conventional concrete has been studied using field and accelerated aging data (Micelli and Nanni 2004; Nanni et al. 2014). Concrete cores with GFRP bars from a bridge in service for 15 years have been extracted and no significant changes in GFRP microstructural properties, chemical composition, glass transition temperature (T_g), and fiber content were observed (Gooranorimi and Nanni 2017). A study on GFRP bars in five to eight year old concrete structures exposed to natural environments did not show any changes in the resin matrix and T_g of extracted GFRP bars compared to GFRP bars preserved under controlled laboratory conditions (Mufti et al. 2007). Based on these results, it was concluded that GFRP bars were "intact" after being in service for that specific period of time.

Several studies have employed elevated temperature as the acceleration factor in order to examine durability of GFRP reinforcement in concrete structures (Chen et al. 2007; El-Maaddawy et al. 2016; Katsuki 1995; Micelli and Nanni 2004; Murphy et al. 1999; Porter 1997; Robert and Benmokrane 2013). Degradation of GFRP bars mainly depends on the alkali diffusion and silica dissolution rates in alkaline environment, both of which are accelerated by elevated temperatures (Byars et al. 2003; Robert et al. 2009). The Arrhenius model has been used to correlate data from accelerated aging to long-term durability of GFRP bars (Bank et al. 2003). Most studies addressed aged bars in simulated concrete pore solutions (Katsuki 1995; Micelli and Nanni 2004; Murphy et al. 1999; Porter 1997), but only few studies were performed on GFRP bars embedded in concrete, which better represents field conditions (Chen et al. 2007; El-Maaddawy et al. 2016; Robert and Benmokrane 2013). Even fewer studies have been performed on GFRP bars embedded in concrete and exposed to saline solutions, which represents marine conditions (El-Maaddawy et al. 2016;

Robert and Benmokrane 2013). While the exposure conditions chosen here are reasonably close to marine conditions, they do not exactly represent marine conditions due to use of higher temperatures and uncracked sections which are not loaded or fatigued. Recent efforts to predict the service life of GFRP bars using Arrhenius model, applied to the data collected by accelerated ageing in seawater at temperatures up to 60 °C, have been inconclusive (Kampmann et al. 2018). It has been suggested that an Arrhenius approach may not be applicable due to the complicated physicochemical degradation mechanism of GFRP bars immersed in seawater at high temperatures. This is in contrast with the underlying assumption of a single component chemical reaction of the Arrhenius model.

A study of mortar-wrapped GFRP bars immersed in 3% NaCl solutions at 23, 40, 50, and 70 °C for 365 days did not show significant degradation in tensile properties and microstructure, even at high temperatures (Robert and Benmokrane 2013). The residual strength of two types of GFRP bars embedded in seawater-mixed concrete immersed in tap water at 20, 40, and 60 °C for 450 days has been studied (El-Maaddawy et al. 2016). The authors found different performance for two types of GFRP bars – tensile strength reduction was 2 – 15% for the GFRP bar Type I and 19 – 50% for GFRP bar Type II (El-Maaddawy et al. 2016). In agreement with other literature (Nanni et al. 2014; Ruiz Emparanza et al. 2017), the authors concluded that durability of GFRP reinforcement is highly dependent on the bar void content and moisture absorption, which are affected by chemical composition of the resin, characteristics of the fiber-resin interface, and interfacial imperfections that may develop during the manufacturing process.

Despite the vast amount of research on GFRP bar durability (Abbasi and Hogg 2005; Bank et al. 1998; Bank et al. 1998; Chen et al. 2007; Hao et al. 2009; Robert and Benmokrane 2010; Zhou et al. 2012), the long-term properties of the bond between GFRP bar and concrete have not been studied in detail (Chen et al. 2007; Robert and Benmokrane 2010). To the authors' best knowledge, this has never been studied with seawater-mixed concrete. It is unclear whether the high concentrations of certain ions (i.e., chloride, sodium, potassium, etc.) in the seawater might result in a reduced durability of the GFRP reinforcement.

The current study evaluates the durability of GFRP bars embedded in seawater-mixed concrete and conventional concrete and immersed in seawater at 60 °C for 24 months. Residual mechanical properties (i.e., tensile properties, horizontal and transverse shear strengths, and bond strength) of the GFRP bars, and the reasons behind their degradation are discussed.

Experimental Materials and Methods

Characterization of Raw Materials

Concrete – A type II cement meeting the requirements of ASTM C150/C150M-19a (ASTM 2019) and a type F fly ash conforming to ASTM C618-19 (ASTM 2019) were used in this study. Tap water and seawater from Key Biscayne Bay (FL) were used as mixing water, respectively, with chemical composition (determined by inductively coupled plasma) as shown in Table 1. Further details are presented elsewhere (Khatibmasjedi et al. 2016). Miami oolite with a nominal maximum aggregate size of 25 mm was used as the coarse aggregate and silica sand as the fine aggregate.

GFRP – The bars were made of boron-free E-CR glass fibers embedded in a vinyl ester resin. The bar manufacturer did not disclose the presence and amounts of fillers and additives to the resin system other than stating that the GFRP bars are in compliance with AC 454 (ICC-ES 2015). The bars had a double helically twisted wrapped fiber as a surface enhancement. 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 2. It should be noted that these bars are compliant with ASTM D7957/D7957M—17 (ASTM 2017) as shown in Table 2. Further details on the testing of GFRP bars are presented elsewhere (Nanni et al. 2014). Five repetitions were performed for each test and the coefficient of variation (CoV, %) for the collected data is also provided in Table 2. A close-up picture of the GFRP bar used in this study is shown in Figure 1.

Concrete Mixtures

Reinforced concrete specimens from two different mixtures with the water to cementitious materials ratio of 0.40 were cast: Mix A is the reference conventional concrete, and Mix B is the seawater-mixed concrete. The mixture proportions of Mix B are identical to those of Mix A, but fresh water is substituted with seawater from Key Biscayne Bay (Florida). Table 3 shows the mixture proportions. The 28-day compressive strength values of Mix A and Mix B were 52.5 and 53.1 MPa, respectively. Further details about the concrete are presented elsewhere (Khatibmasjedi and Nanni 2017).

Durability of GFRP Bars in Seawater Concrete

Accelerated Aging – For all tests except the bond strength test, GFRP bars were embedded in concrete elements (beams) made from the two mixtures with dimensions of 152 x 190 x 1,422 mm with a minimum 30 mm concrete cover. Each specimen was reinforced with four GFRP bars, 1,360 mm long, and cured in the lab environment for 28 days. The configuration of the reinforced specimens is shown in Figure 2. Three concrete specimens were tested immediately after 28 days of lab curing to measure the benchmark properties. The rest of the concrete specimens were 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 (Robert et al. 2009). Aside from self-weight, no load was applied to the beams, therefore, beams were uncracked during conditioning. Every six months, elements were removed from the hot seawater chamber and the bars were extracted from the concrete by splitting the concrete beams using a hammer drill. Extreme caution was exercised in the extraction so as not to damage the bars. Extracted bars were tested in terms of residual tensile properties and horizontal and transverse shear strength as indicators of degradation due to exposure. ASTM test methods were used with at least three repetitions per test. Tests were performed at room temperature 48 hours after the extraction. This time period is needed to install the steel-pipe anchors for tensile tests; all specimens were dried at room temperature for 48 hours before mechanical tests.

Tensile Properties – The ultimate tensile strength and tensile chord modulus of elasticity of extracted GFRP bars after 6, 12, 18, and 24 months exposure to the combination of concrete environment and accelerated conditioning were examined per ASTM D7205/D7205M-06(2016) (ASTM 2016). Steel-pipe anchors were installed using rapid set cement paste and each specimen was instrumented with a linear variable differential transformer (LVDT) to capture elongation during testing. The test setup to measure the tensile properties is shown in Figure 3(a).

Horizontal Shear Strength – The horizontal shear strength of the extracted GFRP bars was determined per ASTM D4475-02(2016) (ASTM 2016). GFRP segments, 82 mm long (span-to-diameter ratio of five) were center-loaded. The ends of the specimen rested on two supports that allowed the specimen to bend. Figure 3(b) shows the test setup to measure the horizontal shear strength. The load was applied at a rate (of crosshead motion) of 1.3 mm/min. The specimen was deflected until shear failure occurred at the mid-plane of the horizontally-supported bar.

<u>Transverse Shear Strength</u> – Extracted GFRP bars were cut into 228-mm long segments and fitted into a double-shear fixture with appropriate cutting blades and clamped into place as per ASTM D7617/D7617M-11(2017) (ASTM 2017). The shear fixture was then mounted into a universal mechanical testing machine and loaded to failure while recording force and crosshead displacement. The test setup to measure the transverse shear strength is shown in Figure 3(c).

<u>Bond Strength of GFRP Bars</u> – The specimens used for the bond strength were as per ASTM D7913/D7913M-14 (ASTM 2014). For this test, 200-mm seawater-mixed and conventional concrete cubes with the mixture design as in Table 3 and embedded 10-mm diameter GFRP bar (of the same type of bars as the ones detailed in Table 2 and Fig. 1) were cast and cured in the lab environment for 28 days. Bond testing was done at this time, and then again after exposure to seawater at 60 °C at an interval of six months. The reason for using GFRP bars with smaller diameter for this test is to avoid the splitting of concrete specimens which is not the desirable failure. The total bond length was 5d, where d is the bar diameter. The steel-pipe anchor was used at the loading-end and an LVDT was used at the free-end of GFRP bars to measure slip. The bearing surface of the concrete cube was placed in contact with the loading plate. Figure 3(d) shows the test setup to measure the bond strength. Tensile loading at the rate of 20 kN /min was applied and continued until the force decreased and the free-end slip was at least 2.5 mm.

<u>Microstructural Studies</u> – Extracted GFRP specimens were polished using different grit levels (i.e., 180, 300, 600 and 1200) of sandpaper using grinding and polishing equipment. The specimens were then fine polished using a wet-polishing agent and 3 and 1 μm polycrystalline

diamond paste. Prior to imaging, specimens were placed in an oven at 50 °C for 24 h to remove any moisture introduced during polishing. Samples were then cleaned using an ultrasonic cleaner and gold-coated prior to imaging. Scanning Electron Microscopy (SEM) imaging and Energy-Dispersive X-ray (EDX) spectroscopy were utilized to inspect the microstructure and chemical composition of the extracted bars in order to better explain degradation mechanisms, both physical and chemical. Both backscatter and secondary imaging were used. While the exact setting parameters varied, typical settings are: Voltage = 15 kV, Working Distance = 12 mm, Spot Size = 60, Magnification = 500x, and Dead Time = 19 – 23%.

Results and Discussion

Tensile Properties

All specimens failed by rupture as shown in Figure 4(a). The results for the tensile strength and tensile chord modulus of elasticity of the extracted GFRP bars after 6, 12, 18, and 24 months exposure to the combination of concrete environment and accelerated conditioning are presented in Figure 5 and Figure 6, respectively.

Figure 5 shows the change in the tensile strength and reduction percentage (which is the reduction in the value of the property at a certain time with respect to the original value) as a function of immersion time. The chord modulus and reduction percentage as a function of time are shown in Figure 6. From these figures, it is apparent that extracted bars from seawater-mixed concrete show comparable performance with the ones from conventional concrete. The tensile strength and chord modulus of both sets of bars slightly increased over the first six months, which may be due to resin crosslinking due to the elevated temperature of the conditioning (Fergani et al. 2018). Both properties then reduce over time, with reductions of 26 and 21% for extracted bars from conventional and seawater-mixed concrete, respectively, after 24 months exposure. Corresponding reductions in chord modulus are 11 and 12% for extracted bars from conventional concrete and seawater-mixed concrete, respectively. The reduction in the tensile strengths is comparable to the reduction in other properties (discussed later). The general reason for the decrease in tensile strength (and other properties) is likely due to the dissolution of silica in the rebar at high temperature in the alkaline environment of concrete (Mukherjee and Arwikar 2005). More detail is provided in the section on microstructural studies. Our results are in general agreement with literature, though results from the literature show significant variations in the reduction values, depending on bar type, exposure temperature, and exposure solution (Almusallam et al. 2013; El-Maaddawy et al. 2016; Park 2012; Robert and Benmokrane 2013; Robert et al. 2009). El-Maaddawy and co-workers (2016) examined seawater-mixed concrete beams reinforced with GFRP and immersed in tap water at 60 °C for 15 months and found that Type I GFRP bars showed better performance than Type II GFRP bars (2 – 15% reduction compared to 19 – 50% reduction). Mortar-wrapped GFRP bars showed 10% reduction in saline solution for 365 days at 50 °C and 16% reduction in tap water at 50 °C for 240 days, indicating that immersion in the saline solution had no more impact on the durability of GFRP bars than immersion in tap water (Robert and Benmokrane 2013; Robert et al. 2009). Others have shown tensile strength reductions of less than 20% (Almusallam et al. 2013; Park 2012). The tensile modulus of the GFRP bars was not affected by aging in a concrete environment in saline solution or tap water (Robert and Benmokrane 2013; Robert et al. 2009), whereas Almusallam and co-workers (2013) showed 9% or lesser reduction in tensile modulus for GFRP reinforced specimens immersed in tap water, seawater, and alkaline baths at 50 °C for 18 months.

Apart from the differences in conditioning regimes, the scatter in results obtained by various authors can clearly be attributed to GFRP bar constituents and manufacturing. Bars tested were made of E or E-CR glass and more importantly with different resin systems (never disclosed aside from the generic name of vinyl ester) including undisclosed additives and fillers. Furthermore, manufacturing procedures such as speed of pultrusion and degree of curing affect the quality of the final product. Thus, when referring to a GFRP bar, one is only considering a "class" of products rather than a well-defined system and all comparisons to literature suffer from some limitations in studies using GFRP.

Horizontal Shear Strength

GFRP specimens in short beam tests failed in shear as shown in Figure 4(b) (horizontal cracks along the mid-plane of the specimens). Figure 7 shows the changes in horizontal shear strength and reduction percentage as a function of time. One standard deviation on each side of the average is shown by error bars. Comparable performance between extracted bars from seawater-mixed concrete and conventional concrete can be observed. The horizontal shear strength decreases as exposure time increases for similar reasons as the tensile strength decrease. At the end of 24 months exposure, the reductions in the horizontal shear strength are 21 and 26% for GFRP extracted bars from conventional concrete and seawater-mixed concrete, respectively. These numbers are in general agreement with the literature. Fergani and co-workers (2018) examined the effect of sustained load and aggressive environments on the horizontal shear strength and concluded that exposure solution had no significant effect on the strength reduction. Stressed GFRP bars showed better performance with 15% reduction compared to unstressed bars, which showed 25% reduction after 270 days. A reduction of 12% in the horizontal shear strength was reported by Chen and co-workers (2007) for GFRP bars embedded in normal concrete and exposed to simulated high performance concrete pore solution at 60 °C. Bakis and co-workers (2005) examined the effect of $Ca(OH)_2$ environment on the horizontal shear strength of the GFRP bars and steady loss of strength until one year was observed, at which time the strength loss was 25%.

Transverse Shear Strength

Typical failure mode of the GFRP bars subjected to transverse shear strength test is shown in Figure 4(c). Figure 8 shows the changes in the transverse shear strength and reduction percentage as a function of time. Error bars show one standard deviation on each side of the average. A similar trend to the horizontal shear strength is observed here. Performance is comparable between GFRP bars extracted from seawater-mixed and conventional concrete. Transverse shear strength decreases over time due to glass dissolution (Mukherjee and Arwikar 2005), and at 24-month exposure, reduction values are 28 and 25% for bars extracted from conventional concrete and seawater-mixed concrete, respectively. It is not possible to compare these results with those from literature, as to the authors' best knowledge, there is no study that has examined the effect of concrete environment and saline solution on the transverse shear strength of GFRP bars.

Bond Strength of GFRP Bars

Pull out test specimens failed by slippage. Specimens were split in half to check the failure mode. As shown in Figure 4(d), the failure occurs at the interface of the double helically twisted wrapped fibers and the bar core. This is due to the lower shear strength at this interface compared to the concrete shear strength. This is consistent with some of technical literature (Davalos et al. 2008;

Robert and Benmokrane 2010). Specimens tested immediately after curing in the lab environment and the conditioned specimens (immersed in seawater at 60 °C) exhibited the same failure modes. Changes in bond strength and reduction percentage as a function of time is shown in Figure 9. Each error bar shows one standard deviation on each side of the average. The bond strength data at 6 months is not shown as there were issues with the experiments at this age. Subsequent immersion in seawater at 60 °C resulted in 6% increase in the bond strength for conventional concrete and 11% reduction for seawater-mixed concrete after 24 months. The reduction in values for seawater-mixed concrete are in general agreement with the literature. Bazli and co-workers (2017) embedded GFRP bars in four different concrete mixtures and exposed the specimens to seawater at 60 °C for 150 days and observed a reduction in bond strength less than 7%. Park (2012) also reported 2.5 – 6% reduction in the bond strength after 300 days immersion in 3% saline solution at 46 °C. Davalos et al. (2008) reported 3 – 8% reduction in bond strength of three types of GFRP bars embedded in concrete and immersed in tap water at 60 °C for 90 days. Others have observed a reduction between 8 – 10 % (Chen et al. 2007; Robert and Benmokrane 2010). This variability between the results here and in the literature could be related to the type of surface enhancement of the GFRP bar as selected by the manufacturer.

Comparison of GFRP Bar Mechanical Properties

In general, a comparable performance was observed between GFRP bars extracted from seawater-mixed and conventional concrete except for the bond strength. The average values of the two sets of bars for each mechanical property were graphed and are shown in Figure 10. Tensile modulus and bond strength show the least reduction of the tested properties (< 10% at 24 months). Reductions in horizontal and transverse shear are comparable and are around 25% at 24 months.

While the reduction in tensile strength is initially lower than the reductions in the horizontal and transverse shear strength, the values at 24 months are comparable. Bond strength showed a contradictory performance with 6% increase for conventional concrete and 11% reduction for seawater-mixed concrete after 24 months. In order to find an explanation for observed performances the degradation mechanism was studied as detailed in the next section.

Microstructural Studies

SEM was used to explain degradation mechanisms due to accelerated aging. Micrographs from the pristine bars as shown in Figure 11 show areas with large concentrations of defects or voids near the edge (surface) of the bar which are formed during manufacturing. These defects (voids) could provide a pathway for moisture and alkalis which can cause local damage in the form of fiber rupture, resin degradation, and debonding of fiber-resin interface during exposure to saline solutions at high temperatures. An example of such damage close to the edge of the bar is shown in Figure 12(a), which is taken after 12 months of exposure. In such areas, fiber damage and rupture, fiber-resin debonding, and cracks are clearly observed. The interior regions of the GFRP bars stayed intact over time as shown in Figure 12(b), taken after 12 months of exposure. Damage in areas close to the edge of the bar and intact interior areas were observed in GFRP bars embedded in conventional and seawater-mixed concretes at all ages of exposure. While qualitatively the extent of damage in areas close to the edge of the bar increases with time, it was not possible to quantify damage change over time using microscopy, due to spatial and temporal variations. It is noted here that other bars extracted from concrete studied in ongoing work in our lab have also shown such damage, while some bars have not, suggesting that this effect is bar-specific, rather than caused by specimen preparation. Results were qualitatively similar for embedded bars in seawater-mixed and conventional concrete, explaining the similar reduction in tensile properties, horizontal shear, and transverse shear strength seen in both sets of bars. As more areas near the edge are affected, long circumferential cracks form. Figure 13 shows three examples of these circumferential cracks at different enlargements. From the evidence above, it appears that the damage is mostly chemical in nature. The type of damage mechanism is consistent with some technical literature (Bank et al. 1998; Fergani et al. 2018; Mukherjee and Arwikar 2005; Wang et al. 2017). It is however not clear if the degradation is mainly caused by the concrete environment, the seawater curing environment, the high temperature, the rebars themselves, or a combination of these factors. Further research on this topic is ongoing.

EDX was used to find possible patterns in the chemical compositions of the damaged areas. Similar silicon and aluminum contents were observed for GFRP bars extracted from conventional and seawater-mixed concrete. The mass percentages of silicon and aluminum in areas at the bar center on average did not reduce (an increase of 3 % was observed for both elements at 24 months when averaging out bars extracted from conventional and seawater-mixed concrete). On the other hand, for areas close to the edge, silicon and aluminum mass percentages reduced 13% and 20%, respectively (average of bars extracted from conventional and seawater-mixed concrete after 24 months of immersion in seawater at 60 °C). These results were obtained from EDX performed on "bulk" areas chosen randomly at 500x magnification, they suggest that the glass content (fiber content) is reducing near the bar edge, but not at the bar center. This is likely due to glass dissolution or deterioration, which leads to the loss of silicon and aluminum, due to the presence of moisture, alkalis and high temperature. This is consistent with literature showing that damaged fibers show about 20% lower silicon and calcium contents compared with undamaged fibers (Mukherjee and Arwikar 2005). Such glass deterioration is due to breaking of the molecular structure of the fiber due to contact with a degenerating agent. While the use of SEM and EDX has provided some insights into the damage mechanism, full clarity is not available, in part because of experimental variability in these techniques. Combining SEM EDX with Fourier-transform infrared spectroscopy and inductively coupled plasma may be further beneficial in fully explaining damage mechanisms in such situations.

Generally, the reductions of tensile strength, horizontal and transverse shear are around 25% for both sets of concrete at 24 months and the reductions in tensile modulus and bond strength are lower at around 10%. A general comparison with literature has been shown in the previous section and these results appear to be consistent with literature – tensile and shear properties reduce more than the bond and tensile modulus. The explanation for this is unclear and quantitative analysis of microstructural damage in terms of damage extents in the bar surface, fiber, resin, and the interface, could be the key in explaining this phenomenon. Alternatively, one could construct a composite model which simulates the rebar based on increasing damages to each individual element (bar surface, fiber, resin, and the interface) to generate and explain the damage in bulk properties.

Conclusions

The durability of seawater-mixed concrete exposed to seawater at high temperatures was studied and contrasted to the behavior of conventional concrete exposed to the same conditions. The following conclusions can be drawn from this study:

a) Extracted GFRP bars from the conventional and seawater-mixed concrete showed comparable performance indicating that using seawater to replace freshwater in mixing concrete has no negative impact on the durability of GFRP bars.

b) After 24-month immersion in seawater at 60 °C, tensile strength decreased by 21 – 26%, tensile modulus by 6 – 12%, horizontal shear strength by 21 – 26%, and transverse shear strength by 25 – 28%.

c) The bond strength showed some differences in performance based on concrete mixture, with 6% increase for conventional concrete and 11% reduction for seawater-mixed concrete at 24 months.

d) Micrographs showed a large number of defects (voids) near the edge of the bars which may have been formed during manufacturing. These defects (voids) provide a pathway for alkalis which can cause local damage in the forms of fiber disintegration and de-bonding between fibers and resin matrix. More fibers are affected over time, leading to circumferential cracks near the edge and subsequently degradation of the edge (surface).

e) SEM results were qualitatively similar for embedded bars in seawater-mixed and conventional concrete, explaining the similar reduction in tensile properties, horizontal shear, and transverse shear strength seen in both sets of bars. However, the contradictory performance of the bond strength cannot be explained without quantitative microstructural analysis.

The GFRP bars tested in this study were ASTM D7957/D7957M-17 (ASTM 2017) compliant and are available in the market and are being used in real-life projects. While this is accelerated testing and the results need to be compared with field data, this suggests that a careful analysis and study of bars under several testing conditions is required before deployment. In addition, the data scatter that we have shown when comparing to literature suggests that generic statements about “all” bars are not possible. Unless industry develops consensus standards on composition, manufacturing and type of surface enhancement for bond with concrete, each commercially available GFRP bar system will have to be thoroughly tested in order to assess its performance and long-term durability.

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Figure Captions List

- **Fig. 1.** Close-up picture of the GFRP bar
- **Fig. 2.** Configuration of the reinforced specimens
- **Fig. 3.** Test setups to measure (a) tensile properties, (b) horizontal shear strength, (c) transverse shear strength, (d) bond strength
- **Fig. 4.** Typical failure mode of the GFRP bars subjected to (a) tensile strength test, (b) horizontal shear strength test, (c) transverse shear strength test, (d) pull out test
- **Fig. 5.** Tensile strength and reduction percentage (error bars for all the figures are equal to one standard deviation of the average value)
- **Fig. 6.** Tensile chord modulus and reduction percentage
- **Fig. 7.** Horizontal shear strength and reduction percentage
- **Fig. 8.** Transverse shear strength and reduction percentage
- **Fig. 9.** Bond strength and reduction percentage
- **Fig. 10.** Average reduction percentage of mechanical properties
- **Fig. 11.** Representative micrograph of the pristine bar
- **Fig. 12.** (a) Representative damaged area near the edge (b) representative intact interior area
- **Fig. 13.** Representative circumferential cracks near the edge (a) x30 (b) x150 (c) x220 magnification

Table 1. Chemical composition of tap water and seawater used in concrete mixtures

Ions	Concentration (ppm)	
	Tap Water	Seawater
Calcium	90	389
Chloride	44	18759
Iron	-	0.512
Potassium	6	329
Magnesium	6	1323
Sodium	26	9585
Sulfate	8	2489
Nitrate	1	0.134

Table 2. Physical and mechanical properties of the pristine bars

Material Property		ASTM Standard	Unit	Value	CoV%	ASTM D7957 Limit
Physical	Cross-sectional area	D792	mm^2	220.9	0.66	186 ≤ A ≤ 251
	Fiber content	D2584	% vol.	76.2	0.82	≥ 70
	Moisture absorption in 24 hours	D570	%	0.23	5.90	≤ 0.25
	Glass transition temperature	E1356	°C	149.7	1.23	≥ 100 °C
	Degree of cure	E2160	%	97.8	0.50	≥ 95
Mechanical	Ultimate tensile force	D7205	kN	250.0	2.20	≥ 130
	Tensile modulus of elasticity	D7205	GPa	52.7	3.50	≥ 44.8
	Horizontal shear strength	D4475	MPa	35.5	3.00	N/A
	Transverse shear strength	D7617	MPa	181.0	5.20	≥ 131

Table 3. Mixture proportions

<table>
<tr><th>Material</th><th>Units</th><th>Mix A</th><th>Mix B</th></tr>
<tr><td>Portland cement I-II (MH)</td><td>kg/m³</td><td colspan="2">332</td></tr>
<tr><td>Fly ash</td><td>kg/m³</td><td colspan="2">83</td></tr>
<tr><td>Tap water</td><td>kg/m³</td><td>168</td><td>-</td></tr>
<tr><td>Seawater</td><td>kg/m³</td><td>-</td><td>168</td></tr>
<tr><td>Coarse aggregate</td><td>kg/m³</td><td colspan="2">1038</td></tr>
<tr><td>Fine aggregate</td><td>kg/m³</td><td colspan="2">612</td></tr>
<tr><td>Set retarding admixture</td><td>ml/m³</td><td>-</td><td>830</td></tr>
<tr><td>Air-entraining admixture</td><td>ml/m³</td><td colspan="2">310</td></tr>
</table>