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Article

Evaluation of the Bond-To-Concrete Properties of GFRP Rebars in Marine Environments

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Abstract: Increased traffic in combination with growing environmental impacts, have led to accelerated degradation of the built infrastructure. In reinforced concrete structures, the corrosion of steel reinforcement is the predominant cause of deterioration. Thus, over the last years the use of glass fiber reinforced polymer (GFRP) composites as internal reinforcement bars (rebars) for concrete structures was evaluated, and has been proved to be a viable alternative to traditional steel reinforcement mainly due to its tensile strength and non-corrosive nature. However, thus far, the GFRP rebar market is diverse and manufacturers around the world produce GFRP rebar types with different surface enhancement to improve the bond to concrete characteristics. In this study, the bond performance of three dissimilar GFRP rebar types (sand coated, helically grooved and with surface lugs) was evaluated over time in seawater environments, with a focus on the bond strength. Accordingly, specimens were expose to seawater in circulating chambers, at three different temperatures (23 °C, 40 °C and 60 °C) for multiple time periods (60 and 120 days). To evaluate the bond performance, pullout tests were conducted according to ASTM D7913 [1]. The results showed that the bond strength varies with surface enhancement features. However, the bond strength didn't vary significantly with exposure time and temperature for all three evaluated rebar types.

Keywords: GFRP rebars; Durability; Bond; Temperature; Surface enhancement

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1. Introduction

Over the last three decades, the use of glass fiber reinforced polymer (GFRP) rebars has been successfully used as an alternative to the traditional steel reinforcement for reinforced concrete structures [2]. A need for this is mainly attributed to the corrosion resistance, unlike steel rebars. This is why the Florida Department of Transportation (FDOT) and other North American institutions are investing in the development of this alternative technology for its use in coastal applications, where corrosion is the principal cause of deterioration [3-5]. In addition to the corrosion resistance, GFRP rebars offer high tensile strength (2-3 time higher than steel rebars), are lightweight (1/4 of the weight of steel), and they are transparent to magnetic fields [6].
GFRP rebars are composite elements made from longitudinal glass fibers embedded in a resin matrix, which can be Vinyl Ester or Epoxy, and are manufactured using 'pultrusion'. The bond between the

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GFRP rebars and the concrete is obtained through various surface treatments used by different manufacturers. One of the biggest issues for the full development of this technology, is the lack of standardization; today the GFRP rebar market is diverse, where different producers manufacture rebars with different cross-sections (round, oval, quadratic, etc.) and dissimilar surface enhancements (sand coating, helical wrap, lugs, etc.) [2]. This last feature is one of the most critical one during the design of GFRP reinforced concrete structures, because proper bond is essential for the composite action of the reinforced concrete system. In design, the coefficient that reflects the bond behavior of the different rebar types is the k_v or bond factor [7]. Although previous studies have evaluated and optimized the bond coefficient (k_v) [8], bond durability and its effects on the system have not yet been studied.

2. Problem Statement and Research Significance

In civil engineering, the resilience of the built infrastructure is crucial and has to be ensured throughout a service life period defined by codes. For GFRP reinforced concrete structures, to-date, different studies have separately verified the durability of the concrete and the GFRP reinforcement [3, 4]. However, not enough research exists to determine the deterioration of the interface between both elements over time in aggressive environments, such as, salt water.

The purpose of this research work is, to analyze and characterize the bond behavior of three different GFRP rebar types (with their respective surface enhancement), and to quantify the degradation of this mechanical property due to harsh salt water environments found in coastal areas. The results will provide deeper insight on this mechanical property and help future researchers to optimize design coefficients such as the bond factor (k_v) or the environmental factor (C_E), while taking the durability of the bond into account. This will lead to a more effective design of reinforced concrete structures with non-corrosive reinforcement.

3. Materials and Methods

In this research project, the bond behavior of three commercial GFRP rebars was studied. To evaluate the bond behavior, the pull-out method proposed by the American Concrete Institute, ASTM D7913 [1], was used.

3.1. Materials

Before the bond tests were conducted, both the concrete and the GFRP bars were characterized individually for bench mark values and quality control. Likewise, these values were used to characterize the overall bond performance.

3.1.1. Concrete

The pullout specimens were made from structural concrete that the Florida Department of Transportation (FDOT) requires for the construction of bridge decks in Florida, USA. This concrete, known as 'Classe II 4500 Bridgedeck', has a guaranteed compressive strength of 4500 psi (31.03 MPa). To obtain the compressive strength of the concrete, companion specimens were tested according to ASTM C39 [9]. At different maturity levels (3d, 7d, 14d and 28d after the concrete was cast), five cylindrical concrete specimens were evaluated, resulting a compressive strength at 28 days of 37.20 MPa with a standard deviation of 0.67 MPa (coefficient of variation of 1.8%).

3.1.2. GFRP rebars

Three types of commercially available rebars were used, all with a nominal diameter of 10 mm and different surface enhancements (see Figure 1).

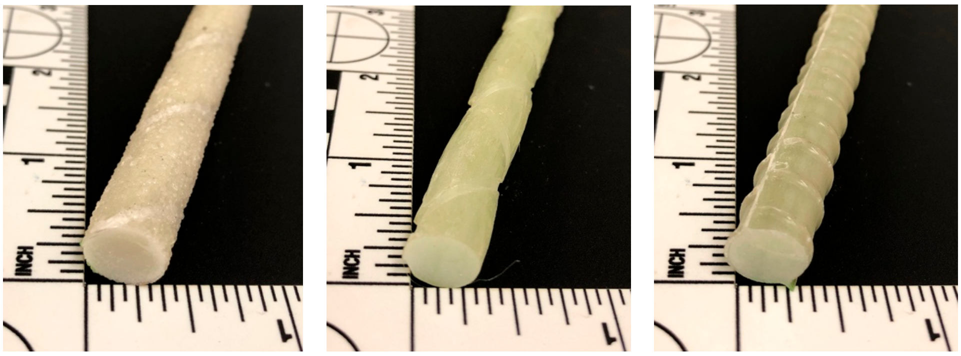

Figure 1. GFRP rebar types A, B and C

These bars were characterized in the materials and structures laboratory at the University of Miami and the FAMU-FSU College of Engineering. The following values were obtained:

Table 1. Properties of the GFRP rebars

Rebar type	Nominal diameter	Measured diameter	Surface enhancement	Tensile strength	Elastic modulus
	mm	mm		MPa	GPa
A		10.17	Sand coating	826.00	45.37
B	10 mm	10.45	Helical wrap	550.20	50.68
C		9.58	Lugs	804.62	51.37

The actual diameters were measured according to ASTM D792 [10], while the guaranteed maximum tensile strengths and the modulus of elasticity were measured per ASTM D7205 [11].

3.2. Specimen preparation

In total, 63 specimens were prepared for the 'pullout' test procedure as described in ASTM D7913 [1]. The loaded end of the rebar (the end were the load was applied) was protected with a 300 mm long steel pipe to shield the rebar from the grips. This was necessary due to the low transverse strength of the FRP rebars. The other end of the rebar, however, was embedded in a 200 x 200 x 200 mm concrete cube. To break the bond between the rebar and the concrete, 150 mm of the rebar (inside the cubes) were shielded to guarantee a pure bond length of 5 times the diameter (50 mm in this case). The samples were casted using individual plywood molds, where fresh concrete was placed in two layers (each layer was equally compacted with an internal vibrator). The samples were demolded after 2 days, and left to cure at ambient conditions for 28 days before the samples were tested or exposed to the aging environments.

3.3. Aging conditioning protocol

To accelerate the deterioration of the bond between the GFRP rebars and the concrete, the specimens were exposed to seawater at different temperatures. Out of the 63 specimens, 54 were submerged in seawater tanks (see Figure 2), while the remaining nine were tested in their virgin state without conditioning, to obtain control values for the analysis of the potential deterioration (see Table 2).

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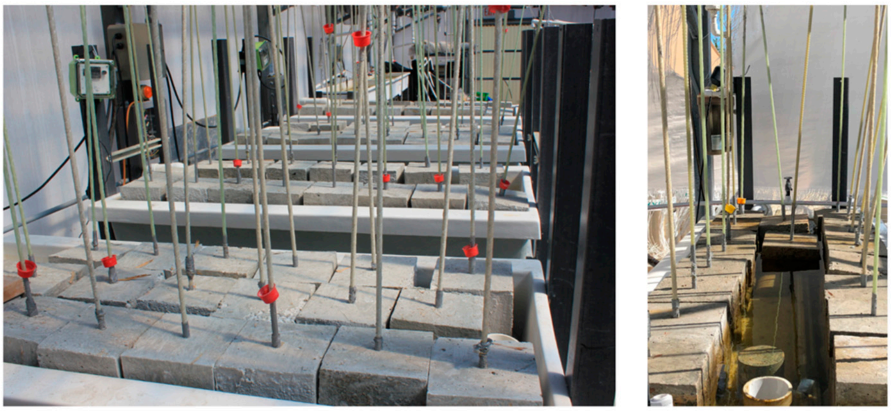

Figure 2. Conditioning exposure of the specimens

The specimens were exposed to three different environments: out of the 54 specimens that were submerged in seawater, 18 were exposed to 23 ° C, 18 to 40 ° C and the last 18 to 60 ° C. Each group of 18 rebars was formed by six rebars of each type (A, B and C).

3.4. Test and instrumentation

The specimens were tested following the method proposed in ASTM D7913 [1]. The tests were conducted in displacement control mode in a universal test frame with a capacity of 890 kN. The load-displacement development throughout the test was monitored and the bond behavior after the maximum load was reached ('post-failure' behavior) was recorded. The load was applied through a displacement rate of 0.5 mm / min. The applied load was recorded by the load cell integral to the test frame, while the displacement was recorded using three displacement transducers or LVDTs: two of them were placed on the loaded end of the rebar, while the third one was placed on the lower part of the concrete cube or free end of the rebar, as it can be seen in Figure 3.

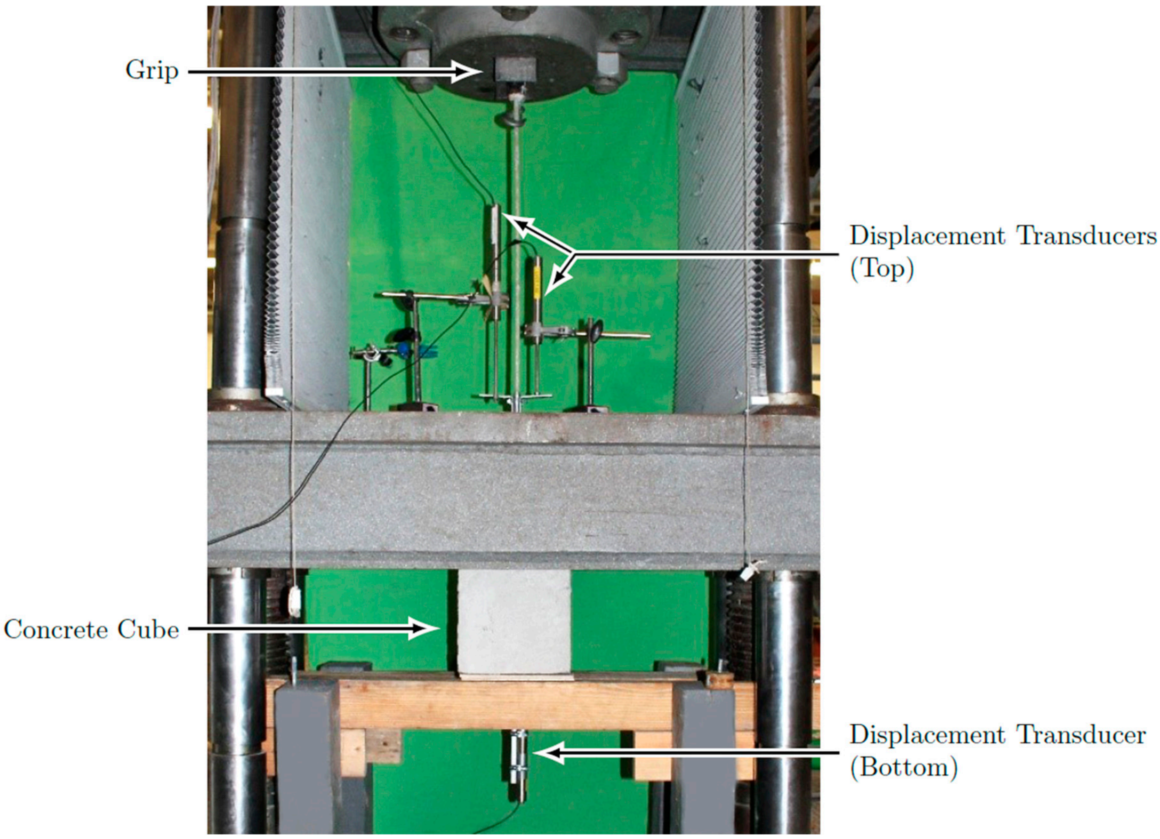

Figure 3. 'Pull-out' test setup

The data for both parameters (load and displacement) was recorded using an automatic data acquisition system with a data rate of 10 Hz. The results were filtered via Butterworth methods.

4. Results and discussion

The experimental results obtained from the 63 specimens tested, were analyzed following the specifications defined in ASTM D7913 [1]. The bond strength was computed using the following equation (1):

$$\tau = F/(C_d \cdot l), \tag{1}$$

Where 'τ' is the average bond strength (MPa), 'F' is the maximum applied load (N), 'l' is the bond length (mm) and 'C_d' is the effective circumference, $\pi \cdot d_b$ (mm).

Prior to the analysis of the aged bond properties of the GFRP rebars, the bond behavior of unaged bond specimens was evaluated. Figure 4 shows the bond strength vs. free-end slippage of each of the tested unaged composite rebars.

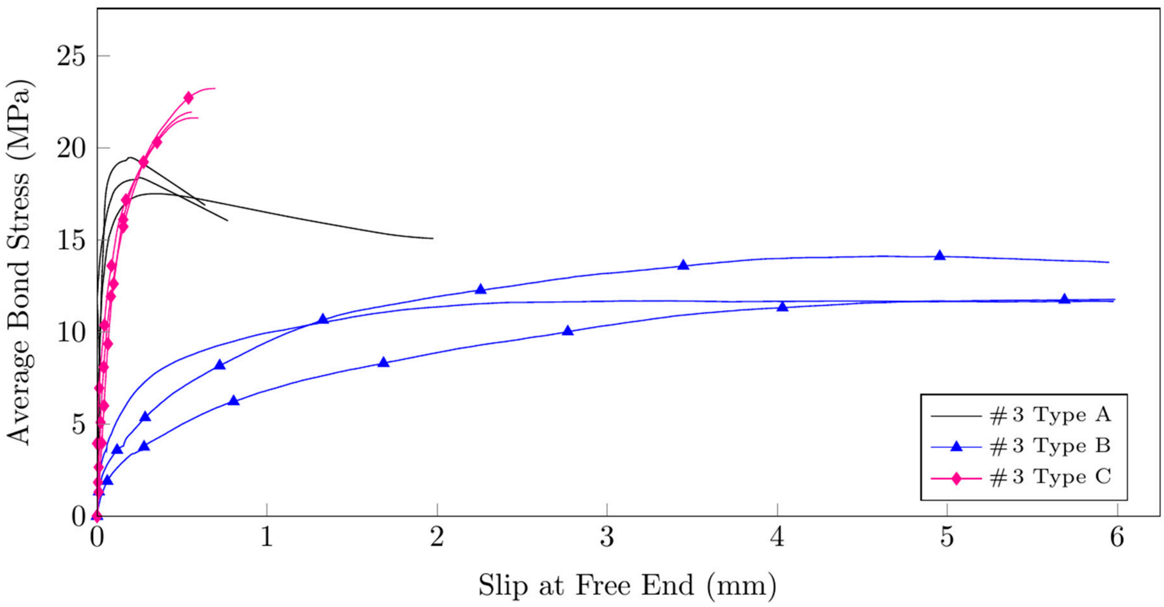

Figure 4. Bond-slip (free-end) behavior of unaged samples

It can be inferred, that the bond-to-concrete behavior varied from rebar type to rebar type, as seen from the bond-slip graph; the initial slope, peak stress, slippage values and 'post-failure' behavior characteristic for each bar type. The ribbed rebars (type C) developed the highest maximum bond strength with value of approximately 22.5 MPa; these were followed by the sand coated bars (type A) with about 18 MPa, while rebars with external cross fibers (type B) measured values ranging around 12.5 MPa. The peak bond strength for type A rebars was reached at a free-end slippage of about 0.25 mm, and after the peak, the bond strength decreased almost linearly. For rebars type B, the free-end slippage corresponding to the maximum bond strength, was about 20 times higher than the one for type A rebars (reaching approximately 5 mm). In this case, after the peak bond was reached, the bond strength decreased gradually. The 'post failure' behavior pf type C rebars, however, was dissimilar to the one of rebars type A and B: as soon as the maximum bond strength for the ribbed and sand coated rebars was attained (at about 0.7 mm), a sudden failure of the bond surface occurred.

After the bond behavior of the three GFRP rebar types was evaluated, the durability of this mechanical property was assessed on test samples that were stored in seawater for different exposure times and temperatures. Accordingly, the potential fluctuation of the maximum bond strength over time was analyzed. Table 2 shows the average values of the "pull-out" peak load, as well as the average maximum bond strength values for the different bars and different exposure conditions.

Table 2. Experimental maximum values of the bond between the GFRP rebars and the concrete

Rebar type	**Exposure time**	**Temperature**	**'Pull-out' load (average)**		**Bond strength (average)**	
			kN	kip	MPa	ksi
A	cc	cc [1]	29.37	6.60	18.39	2.67
	60d	23	23.54	5.29	14.73	2.14
		40	29.46	6.62	18.44	2.68
		60	26.03	5.85	16.29	2.36
	120d	23	25.04	5.63	15.68	2.27
		40	23.46	5.27	14.68	2.13
		60	25.32	5.69	15.85	2.30
B	cc	cc [1]	30.77	6.92	18.75	2.72
	60d	23	26.70	6.00	16.26	2.36
		40	27.64	6.21	16.84	2.44
		60	29.82	6.70	18.17	2.64
	120d	23	32.67	7.35	19.90	2.89
		40	32.22	7.24	19.63	2.85
		60	28.15	6.33	17.15	2.49
C	cc	cc [1]	33.52	7.54	22.28	3.23
	60d	23	28.01	6.30	18.62	2.70
		40	31.16	7.01	20.71	3.00
		60	30.98	6.97	20.59	2.99
	120d	23	31.92	7.18	21.21	3.08
		40	29.61	6.66	19.68	2.85
		60	30.00	6.74	19.93	2.89

[1] control values (non-aged specimens)

For a better interpretation of the results, Figure 4 shows the evolution of the maximum bond strength values for the three types of bars exposed to 23, 40 and 60 ° C. The bond of Type-A bars after 60 days of exposure, suffered a deterioration of around 10% in the case of the samples exposed to seawater at 60 ° C, 18% at 23 ° C, and it remained unchanged at 40 ° C. After 120 days, the three conditions converged to a deterioration of around 15%. The deterioration of Type-B rebars, however, remained effectively constant after 60 days of exposure for the three different temperatures. After 120d, an increase in the bond capacity of around 15% was noted in the case of exposures of 23 and 40 ° C, while the bond strength of the specimens exposed to 60 ° C, dropped by 5%. For Type-C rebars, after 60 days of exposure a deterioration of 5% was detected at 40 and 60 ° C, compared to 10% in the

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case of exposure to 23 ° C. After 120 days, on the contrary, a bond increase of 12% was noted for the rebars exposed to 23 ° C while those exposed to 40 and 60 ° C suffered an additional 5% deterioration.

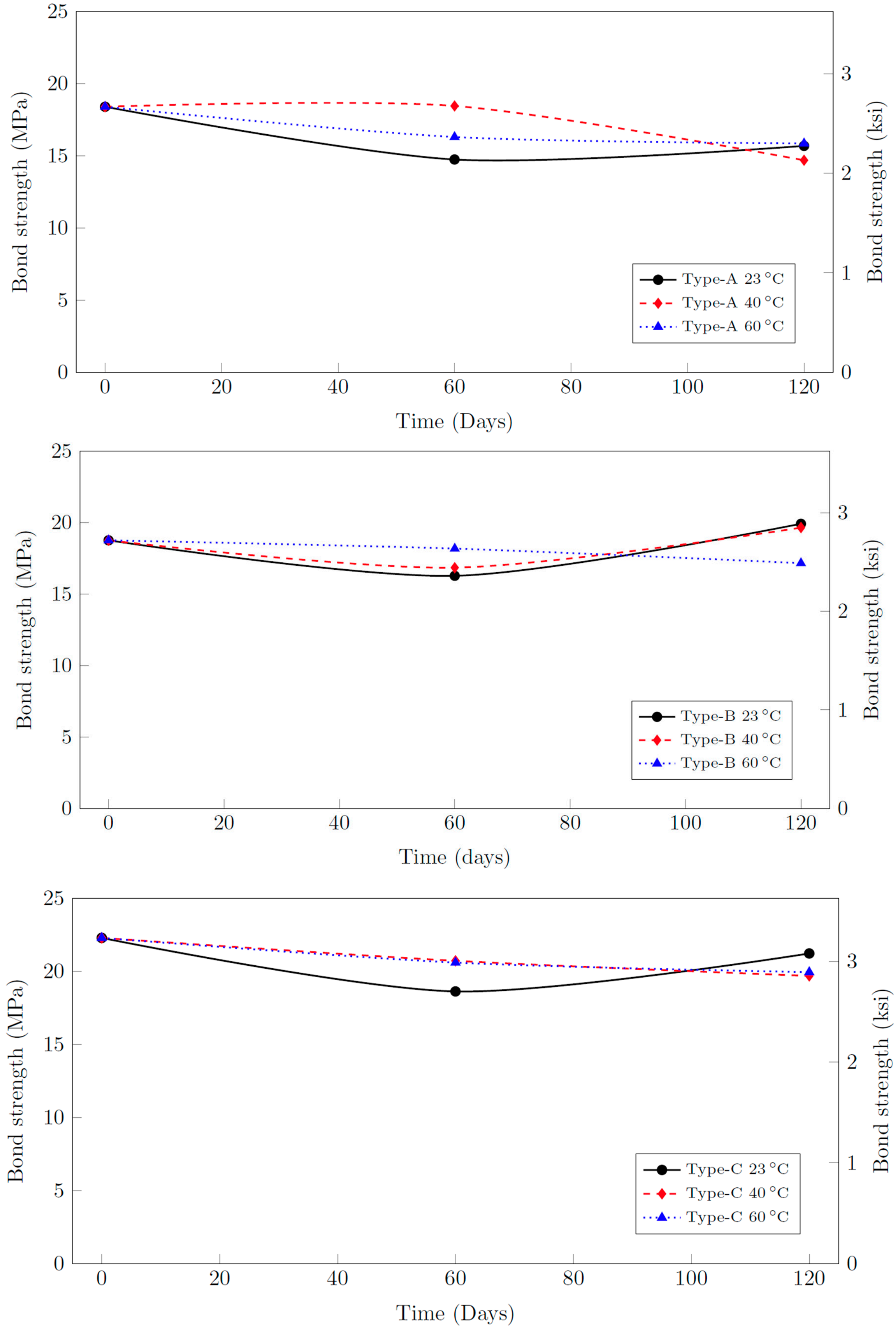

Figure 4. Bond strength development over time (rebar types A, B and C)

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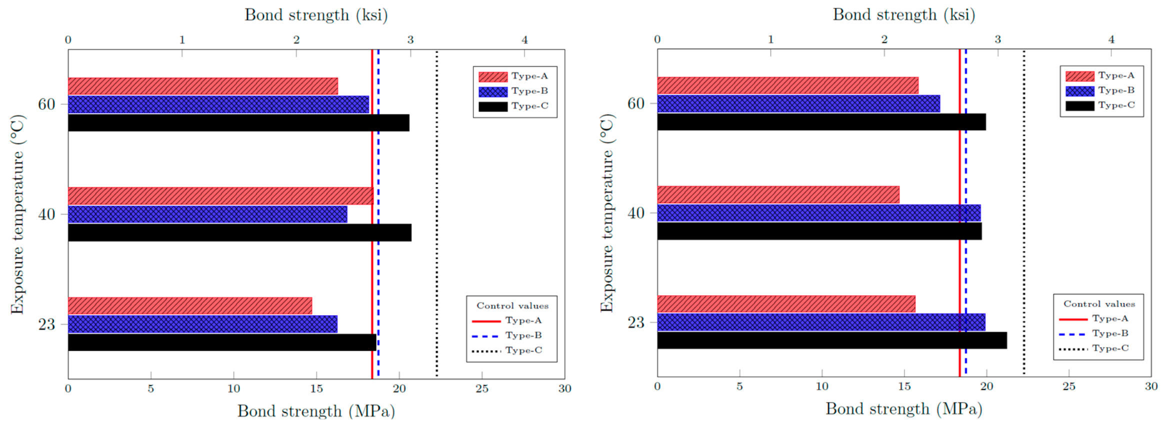
From the three graphs corresponding to the evolution of the bond strength over time, it can be seen that the variation of this mechanical property is not significant after 120 days of exposure to seawater at 23, 40 or 60 °C; the values range between 10% and 15%, including cases with bond strength increase. In addition, the effect of the temperature to accelerate the degradation, does not seem to have caused a significant effect.

The graphs in Figure 5 facilitate a comparison between the three rebar types; it can be inferred that the type C rebar (with lugs) had the highest bond strength, whereas the type A (sand coated) and B rebars (helical grooved) measured similar mechanical bond. The bond deterioration was no more than 15% in all three cases after 120 days of exposure to seawater, regardless the temperature.



(**a**) (**b**)

Figure 5. Bond strength development after 60 (a) and 120 days (b)

4.1. Failure mechanisms

Every specimen tested showed a very similar failure mechanism: in all (both control and conditioned samples), the failure occurred at the bond interface between the GFRP rebar and the concrete. No GFRP rebar failed in tension, nor concrete splitting was observed for any of the tested samples, which differs from the observations made by others [12-14]. After the samples were tested, the concrete blocks were split in half to evaluate the interface surface of the rebar (Figure 6).

(a) (b) (c)

Figure 6. Bond surface of the GFRP rebar after completion of bond test: type A (a), type B (b) and type (c)

It can be seen that the damage of the rebars varied with the type of surface enhancement: for type A rebars, the sand-coat was removed due to the friction between the rebar and the concrete. The type B rebars, however, showed damage in the most superficial fibers, though helical groves were not completely lost. Finally, the lugs in the type C rebars were partially or completely cut off during the pullout test, but the internal glass fibers of the rebar were not exposed to the surface.

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5. Conclusions

The durability of the bond between the GFRP rebars and concrete in coastal environments is a characteristic which, even though it is crucial, has not been fully evaluated, so far. Considering the great importance of this mechanical property in the proper functioning of GFRP reinforced concrete structures, many institutions, such as the Florida Department of Transportation (FDOT), are directing efforts towards its evaluation. As part of these efforts, the bond mechanism of three different types of GFRP rebars (sand coated, helically grooved and with lugs) exposed to a marine environment was evaluated via 'pullout' tests.

The test results showed that GFRP rebars with different surface enhancements perform significantly different from one another and show dissimilar bond-slip behaviors. Within the scope of the tested materials, the ribbed rebars (type C) offered the highest bond strength (22.5 MPa), followed by sand coated (type A) rebars (18 MPa), and rebars with external cross fibers (type B) (12.5 MPa).

The bond stress development is also affected based on the selected rebar types: sand coated rebars (type A) activate the full bond strength rapidly exhibit the stiffest bond with concrete (free-end slippage). Type A rebars were followed by ribbed (type C) rebars, while the highest slippage may be expected for GFRP rebars with external cross fibers (type B); these rebars may slip about 20 times more than rebars with other surface enhancements. After the maximum bond was reached, type A and B rebars gradually debonded, while ribbed bars (type C) promoted a sudden-slip failure.

For durability assessment of the bond strength, additional companion specimens were submerged in seawater tanks at different temperatures (23, 40 and 60 ° C) for 60 and 120 days. Initial results show that deterioration of bond strength may not be severe, though the specimens were tested under accelerated conditions. After 120 days of exposure in seawater at 23, 40 and 60 ° C, the maximum bond strength varied around +/- 10% to 15%.

The bond failure mode of GFRP specimens in concrete depends on the surface enhancement and is independent of the exposure temperature or duration. All specimens failed at the interface between the surface enhancement and the concrete, but each bar type was damaged differently: type A rebars lost the sand coat and then slipped, type B rebars suffered partial damage of the longitudinal external fibers before slip-out, and finally, the lugs of the type C rebars were cut off but the glass fibers remained intact.

Further testing and a larger array of experiments under long-term exposure should be conducted to validate these initial finding or to provide additional data for the bond performance of GFRP reinforced concrete.

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References

1. ASTM International. ASTM D7913 - Standard Test Method for Bond Strength of Fiber-Reinforced Polymer Matrix Composite Bars to Concrete by Pullout Testing. 2014. Epub ahead of print 2014.
2. Ruiz Emparanza A, Kampmann R, De Caso F. State-of-the-Practice of Global Manufacturing of FRP Rebar and Specifications. In: *ACI Fall Convention, Anaheim*. 2017.
3. Robert M, Benmokrane B. Combined effects of saline solution and moist concrete on long-term durability of GFRP reinforcing bars. *Constr Build Mater*; 38.
4. Micelli F, Nanni A. Durability of FRP rods for concrete structures. *Constr Build Mater* 2004; 18: 491–503.
5. Chen Y, Davalos JF, Ray I, et al. Accelerated aging tests for evaluations of durability performance of FRP reinforcing bars for concrete structures. *Compos Struct* 2007; 78: 101–111.
6. Nanni A, Luca A De, Zadeh HJ. Reinforced Concrete with FRP Bars: Mechanics and Design. CRC Press, pp. 23–33.
7. Rossini M, Bruschi E, Matta F, et al. Case-Specific Parametric Analysis as Research-Directing Tool for Analysis and Design of GFRP-RC Structures. In: *ACI Fall Convention, Anaheim*. 2017.
8. El-Nemr A, Ahmed EA, Barris C, et al. Bond-dependent coefficient of glass- and carbon-FRP bars in normal- and high-strength concretes. *Constr Build Mater* 2016; 113: 77–89.
9. ASTM International. ASTM C39 - Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. 2016. Epub ahead of print 2016. DOI: 10.1520/C0039.
10. ASTM International. ASTM D792 - Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement. 2013. Epub ahead of print 2013.
11. ASTM International. ASTM D7205 - Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars. 2011. Epub ahead of print 2011.
12. Gu X, Yu B, Wu M. Experimental study of the bond performance and mechanical response of GFRP reinforced concrete. *Constr Build Mater* 2016; 114: 407–415.
13. Dong Z, Wu G, Xu B, et al. Bond durability of BFRP bars embedded in concrete under seawater conditions and the long-term bond strength prediction. *Mater Des* 2016; 92: 552–562.
14. Okelo R, Yuan RL. Bond Strength of Fiber Reinforced Polymer Rebars in Normal Strength Concrete. *J Compos Constr* 2005; 9: 203–213.