BOND BEHAVIOUR BETWEEN GFRP RODS AND CONCRETE PRODUCED WITH SEAWATER: AN EXPERIMENTAL RESEARCH

José Sena-Cruz [1], Eduardo Pereira [1], Nélson Freitas [1], Emanuel Pereira [1] and Sérgio Soares [1]

[1] *ISISE, Department of Civil Engineering, University of Minho, Portugal (corresponding author: jsena@civil.uminho.pt)*

ABSTRACT

It is unquestionable that water is an indispensable natural resource for the existence of life on planet Earth, holding enormous environmental, economic and social value. Today, with the increase of the population and consequent increase in pollution, drinkable water is an increasingly sought-after and scarce resource. In this context, the need to explore the potential of the direct use of seawater in the production of reinforced concrete (RC) structures becomes evident. On the other hand, since the earliest times of universal history the sea constitutes the most important space in world economic development, to which onshore and offshore structures are associated. Structures when exposed to marine environments (e.g. ports, offshore structures, buildings located by the sea) are subjected to the simultaneous action of several physical and chemical deterioration processes that accelerate their degradation and greatly reduce their service life. With the advent of fibre reinforced polymers (FRP), the construction industry has experienced a revolution due to the countless advantages that these materials present, among which stands out their resistance to corrosion. Therefore, the use of these new materials in RC structures exposed to marine environments may prevent the main damages that aggressive agents typically originate in conventional RC, as well as to allow seawater to be directly used in the design of concrete, thus avoiding the use of drinkable water.

In this work the possibility of using seawater in the design of RC structures, in combination to the use of glass FRP (GFRP) rods, is explored. The research carried out included two phases: (i) the development of concrete compositions including seawater and (ii) the assessment of the bond behaviour between GFRP rods and the developed concrete. The present part is mainly devoted to the second phase where the influence of type of water (tap water or seawater), the GFRP diameter and anchorage length on the bond between GFRP rods and concrete were investigated. The main results obtained have shown that the use of seawater in the concrete composition had no severe effects on the mechanical properties of the concrete and on the bond behaviour between the GFRP rods and the concrete.

KEYWORDS

Bond behaviour, GFRP rods, concrete produced with seawater, direct pullout tests.

INTRODUCTION

The drinkable water is an increasingly scarce resource. The oceans constitute about 80% of the earth's surface which means that about 98% of the water on the planet is salty. The use of tap water in concrete production is not sustainable, considering that in many latitudes it is considered as a rare resource. In this context, the possibility to use seawater directly in the design of reinforced concrete structures (RC) is of great potential. However, RC structures in marine environments are subjected to the simultaneous action of several physical and chemical deterioration processes that accelerate their degradation and greatly reduce their service life. Among many others, corrosion of conventional steel reinforcement and degradation of the concrete cover layer are the most catastrophic effects that result from the exposure to the typically high chlorides concentrations (Ragab et al. 2016; Pradelle et al. 2017). Nevertheless, the emergence of fibre reinforced polymers (FRP) and the replacement of conventional steel by these new materials can lead to the use of seawater in the concrete structures design, due their resistance to corrosion. Furthermore, FRP materials have other advantages such as the high tensile strength, low weight, low thermal conductivity and good fatigue behaviour (Goldston et al. 2017). Therefore, the use of composite materials in reinforced concrete structures design may be combined with the use of seawater, avoiding the consumption of tap water and contributing to more sustainable construction approaches. This topic requires dedicated studies to understand the consequences of using seawater in the concrete production. Till now, scientific knowledge in this area is still limited. Existing studies (Li et al. 2016; Xiao et al. 2017) have shown that the use of seawater may have a significant effect on chloride-induced steel corrosion but has a negligible effect on the carbonation process of concrete. Furthermore, the results showed that the use of seawater increased concrete's compressive strength at early age, reduced setting time and improved mechanical properties. On the other hand, structural behaviour of reinforced concrete elements using composite materials (FRP) has been extensively studied, mainly focusing the bond characterization between FRP and concrete, as well as the flexural and shear behaviour in full-scale reinforced concrete beams. Typically, GFRP (Glass FRP) rods have been used to reinforce concrete elements, e.g. Mazaheripour et al. (2013) and Barris et al. (2017). Some research has been carried out on the study of the long-term behaviour and durability of RC elements with FRP rods, particularly when exposed to alkaline environments, chlorides action, seawater immersion, high temperatures, moisture, thermal cycles and freeze-thaw cycles, e.g. Dong et al. (2016). According to the studies carried out, the use of FRP rods in RC structures exposed to marine environments shows to be very promising not only due to the resulting structural performance but also for the contribution to promoting environmental sustainability.

An ongoing research work by the authors of the present paper is exploring the use of seawater in the concrete production, when the conventional steel reinforcement is replaced by GFRP rods. The research work includes two phases. In the first phase concrete compositions were developed through an optimization algorithm to obtain specific properties at fresh and hardened states. The second phase included experimental investigation on the bond behaviour between GFRP rods and concrete through direct pullout tests. As a result, the influence of the type of water (seawater and tap water) in the concrete mixture, as well as the GFRP rod diameter and anchorage length on the bond behaviour between GRFP and concrete, were assessed.

EXPERIMENTAL PROGRAM

Concrete composition

In this section, the procedure used to determine the concrete composition is briefly described. This composition was used in the production of the concrete pullout test specimens. The objective was to find out the best dosages to produce a concrete with mechanical properties required in special projects requiring higher strengths, particularly in maritime environments. The requirements included: (i) good workability at the fresh state and (ii) high mechanical strength at the hardened state. The concrete composition is mainly influenced by two parameters: (i) water/cement (w/c) ratio and (ii) particle size distribution of the aggregates. The concrete compositions were established based on the work carried out by Pereira (2016), using modifications proposed by Andreasen and Andersen (A&A). The aggregates were carefully selected and previously washed. According the standard NP EN 933-1:2000, the sieve analysis was performed. Once the solids composition was defined, the next step was the analysis of the water/cement (w/c) ratio influence. In order to do so, several mixtures were produced with different w/c ratios. The iterative process included characterization tests in the fresh and hardened state. The composition selected had a w/c ratio of 0.26. Based on the results of the optimization of solids composition, as well as on concrete characterization in the fresh and hardened state, the final composition was: (i) cement CEM I 42.5R according to European standard NP EN 197-1:2001 (480 kg/m^3), (ii) class-f fly ash (124.5 kg/m^3), (iii) sand (1271 kg/m^3), (iv) gravel 4-8 (192 kg/m^3), (v) gravel 8-16 (76.7 kg/m^3), (vi) superplasticizer *Sika® ViscoCrete® 3002 HE* (5.1 kg/m^3) and (vii) viscosity modifying agent *Sika® VP1* (4.8 kg/m^3). The required water to saturate the aggregates was determined for each mixture according to ASTM C566-97:2013.

Direct pullout tests: geometry, experimental set-up, instrumentation and materials characterization

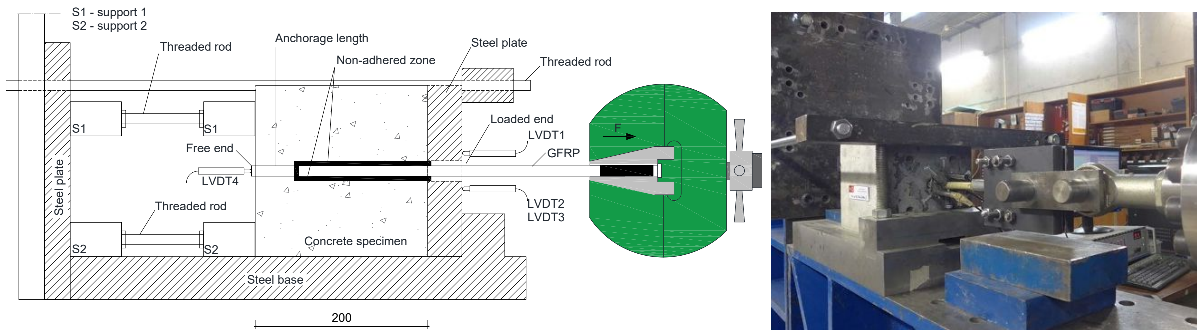
The program was composed of 24 direct pullout tests divided into 8 series. Studied parameters were (i) type of water used in the concrete composition (SW- seawater or TP- tap water), (ii) GFRP rods diameter (Ø8 or Ø12) and (iii) anchorage length (5Ø or 10Ø). The SW used in the concrete production was extracted directly from the sea - in Esposende (north coastal area of Portugal). According to laboratory analyses carried out by *APA-ARH Norte* (Portuguese Environment Agency), the water quality was rated as excellent, without chemical pollutants. The salinity of SW, i.e. salt concentration per unit mass of water is about 3.5 % (Antonov et al. 2006). The experimental program is shown in Table 1. The designation of each series was defined as follows: (i) "Ø" is the GFRP nominal diameter in millimeters, (ii) "LbXØ" is the anchorage length where X is the multiple of GFRP nominal diameter (5 or 10) and (iii) "TW" or "SW" states the type of water used in concrete composition (tap water or seawater, respectively). In each test series, 3 tests were performed under the same conditions.

Figure 1 depicts the test set-up adopted for the present experimental program. Concrete cubic blocks with 200 mm of edge were used. The applied force was measured with a load cell of 200 kN (0.05% F.S.) maximum capacity. The relative displacement between the GFRP and the concrete (slip) at the loaded end section was assessed by the average of displacements measured by LVDTs 1, 2 and 3, positioned at 120º around the GFRP rebar. Free end slip was assessed by the use of LVDT 4. LVDTs 1 and 2 had a stroke of ±10 mm (0.25% F.S.). LVDTs 3 and 4 had a stroke of ±5 mm (0.25% F.S.). Tests were performed under displacement control at a velocity of 0.021 mm/s.

Table 1: Direct pullout tests – experimental program.

Age of concrete [days]	**Water type**	**GFRP rod diameter** [mm]	**Anchorage length** [mm]	**Designation***
28	TW	8	40	Ø8_Lb5Ø_TW_i
			80	Ø8_Lb10Ø_TW_i
		12	60	Ø12_Lb5Ø_TW_i
			120	Ø12_Lb10Ø_TW_i
	SW	8	40	Ø8_Lb5Ø_SW_i
			80	Ø8_Lb10Ø_SW_i
		12	60	Ø12_Lb5Ø_SW_i
			120	Ø12_Lb10Ø_SW_i

* "i" represents the specimen 1, 2 or 3.



(a) (b)

Figure 1 – Pullout tests: (a) scheme; (b) photo. Note: dimensions in millimeters.

Before carrying out the direct pullout tests, the constituting materials were characterized: (i) concrete (with SW and TW) and (ii) GFRP rods.

Concrete was characterized in two different phases: (i) fresh state and (ii) hardened state. To characterize the concrete properties in the fresh state, slump-flow tests were carried out and the T_{500} parameter was measured, according to the standard BS EN 12350-8:2010. This test allows the evaluation of the deformability of the concrete through the deformation velocity and slump flow diameter imposed by the action of self-weight. The T_{500} parameter allows to indirectly assess the concrete viscosity. To produce the concrete for the pullout test specimens, four concrete castings were carried out (two with SW and the others with TW). Each concrete casting was composed of two batches. To characterize the concrete properties in the hardened state, compression tests were carried out with concrete cylindrical specimens. The cylinders had a diameter of 150 mm and a height of 300 mm. Compression tests were carried out 28 days after casting, in order to obtain compressive strength (f_c) and modulus of elasticity (E_c), according NP EN 12390-3:2011 and LNEC E397:1993. In total, eight cylindrical specimens were tested: four with concrete made of seawater and the remaining ones with the concrete made of tap water. All concrete specimens (cylinders for concrete characterization tests and cubes for pullout tests) were cured in a wet environment, fully submerged in a water tank at a temperature of 22±2 °C until the testing day (28 days of age). The type of water (SW or TW) used to submerge the test specimens corresponded to the type of water used in the respective concrete composition. Test results of concrete characterization and corresponding analysis are included in the next section.

ComBAR® GFRP ribbed round rods produced by the company *Schöck* were used. As stated previously, two distinct diameters were studied: 8 and 12 mm. These rods present a deformed external surface with ribs of a constant height of 6% of bar diameter and a spacing of about 8.5 mm. The tensile mechanical properties of these rods were assessed according to the ASTM D7205/D7205M:2006 by conducting uniaxial tensile tests. From six GFRP rods with 8 mm of diameter (Ø8) tested, an average modulus of elasticity of E_f=69 GPa (CoV=3.6%), an average tensile strength of f_{ult}=1527.9 (CoV=4.5%) and an average ultimate strain of ε_f=1.8% (CoV=0.1%), were obtained. From the six samples of GFRP Ø12 rods tested, the following mechanical properties were obtained: E_f=70.1 GPa (CoV=3.1%), f_{ult}=1447.1 (CoV=6.5%) and ε_f=1.8% (CoV=1.0%).

RESULTS AND DISCUSSION

Concrete characterization

Table 2 presents the results of the concrete characterization tests in the fresh state. The results show that when seawater was used in the mixture, the concrete exhibited a more cohesive, viscous and compact behaviour compared to the mixture where tap water was used. Consequently, the concrete with seawater presented worse workability than the concrete with tap water, and for that reason it was not possible to obtain the T_{500} parameter (concrete casting 2 and 3) because the fluid concrete did not reach a flow diameter of 500 mm. All concrete mixtures did not show any sign of segregation. Additionally, the results suggest that the use of seawater in the mixture may have reduced concrete setting time and led to the faster development of its mechanical properties (Freitas 2017). Similar conclusions were obtained in other research studies, e.g. Etxeberria et al. (2016).

Table 2: Fresh state concrete properties.

Concrete casting	Concrete casting 1		Concrete casting 2		Concrete casting 3		Concrete casting 4	
	1st batch	2nd batch	1st batch	2nd batch	1st batch	2nd batch	1st batch	2nd batch
Water	TW	TW	SW	SW	SW	SW	TW	TW
Slump flow [mm]	625.0	612.5	420.5	447.5	330.0	400.0	400.0	485.0
T_{500} [s]	13	15	*	*	*	*	16	15
Photos								

*invalid results.

Table 3 presents the results of concrete mechanical characterization by compression tests in hardened state (28 days of age). In general, the concrete produced with tap water presented better mechanical properties than the concrete with seawater. Seawater contains several mineral and biological elements that can interact with concrete components and consequently influence their properties. The results show that when seawater was used in the mixture, a lower mean compressive strength (f_{cm}) was obtained (≈58 MPa) comparatively to the use of tap water (≈66 MPa). A similar trend was observed in terms of modulus of elasticity: when seawater was used in the concrete mixture, a mean modulus of elasticity (E_{cm}) of 33.7 GPa was obtained whereas the use of tap water has resulted in a mean modulus of elasticity of 36.2 GPa. According to EN 1992-1-1:2010, the concrete with seawater complies with the strength class C50/60; while the concrete with tap water in its composition complies with the strength class C55/67.

Bond behaviour

Average results obtained in each series of the direct pullout tests are presented in Table 4 through several parameters that characterize the bond behaviour between GFRP and concrete. The parameters included are the (i) maximum pullout force (F_{max}), (ii) loaded end slip at F_{max} (s_{lmax}), (iii) free end slip at F_{max} (s_{fmax}), (iv) average shear strength (τ_{max}) assuming a constant shear stress along the anchorage length (ratio between F_{max} and contact area between the GFRP and concrete), (v) residual pullout force corresponding to a s_l of 10 mm (F_r), (vi) fracture energy during debonding process up to 10 mm of s_l (G_f), (vii) F_r/F_{max} ratio and (viii) failure mode observed.

Table 3: Hardened state concrete properties.

Compressive Strength (f_c) **and Modulus of Elasticity** (E_c)		**Tap water** (TW)	**Seawater** (SW)
	$f_{c,28d}$ [MPa]	65.7	61.9
		66.6	57.9
		67.3	54.7
		66.3	57.7
	f_{cm} [MPa]	66.5 (0.9%)	58.0 (4.4%)
	$E_{c,28d}$ [GPa]	36.8	32.3
		36.7	34.4
		37.1	33.0
		34.7	33.7
	E_{cm} [GPa]	36.2 (2.6%)	33.7 (2.3%)

The values in parentheses are coefficients of variation (CoV).

Table 4: Average results obtained from the direct pullout tests.

Serie	F_{max} [kN]	s_{lmax} [mm]	s_{fmax} [mm]	τ_{max} [MPa]	F_r [kN]	G_f [kN.mm]	F_r/F_{max} [%]	Failure Mode*
Ø8_Lb5Ø_TW	19.8 (4.7%)	2.01 (4.2%)	0.39 (25.7%)	13.1 (5.1%)	8.3 (44.0%)	133.0 (22.4%)	41.7 (43.0%)	PF[1,2] TF[3]
Ø8_Lb10Ø_TW	33.7 (2.2%)	3.15 (3.4%)	0.31 (24.1%)	11.2 (2.1%)	34.3 (4.5%)	341.9 (20.5%)	102.0 (6.0%)	TF[1,2,3]
Ø12_Lb5Ø_TW	48.9 (5.8%)	2.06 (7.9%)	0.24 (31.9%)	21.6 (5.7%)	27.7 (28.8%)	317.7 (11.2%)	57.6 (32.6%)	D[1] TF[2,3]
Ø12_Lb10Ø_TW	81.8 (2.5%)	3.25 (3.0%)	0.32 (10.2%)	18.1 (2.5%)	39.4 (18.4%)	494.3 (8.4%)	48.1 (16.6%)	D[1,2,3]
Ø8_Lb5Ø_SW	13.7 (2.4%)	1.37 (1.2%)	0.25 (4.9%)	9.0 (2.6%)	3.2 (24.3%)	60.5 (15.7%)	23.4 (22.3%)	D[1,2,3]
Ø8_Lb10Ø_SW	25.6 (3.3%)	2.34 (5.0%)	0.29 (8.2%)	8.5 (3.3%)	10.6 (10.1%)	151.7 (9.4%)	41.2 (9.4%)	D[1,2,3]
Ø12_Lb5Ø_SW	45.1 (2.3%)	1.89 (2.0%)	0.33 (15.6%)	20.0 (2.3%)	11.6 (11.8%)	210.6 (4.0%)	25.9 (13.4%)	D[1,2,3]
Ø12_Lb10Ø_SW	68.7 (6.9%)	2.60 (7.1%)	0.32 (5.8%)	15.2 (6.9%)	23.3 (8.6%)	354.4 (3.1%)	33.9 (5.7%)	D[1,2,3]

*Failure modes: (TF)-debonding failure at the interface GFRP/concrete + total failure of GFRP ribs; (PF)-debonding failure at the interface GFRP/concrete + partial failure of GFRP ribs; (D)-debonding failure; 1,2,3 is the specimen number; The values in parentheses are coefficients of variation (CoV).

Figure 2 shows the relation between the pullout force (F) and loaded end slip (s_l) obtained in the direct pullout tests. In general, two distinct phases can be identified in the F-s_l curves. The first phase (pre-peak) is characterized by an approximately linear relationship between the applied force and the slip. At this phase, the bond adherence provided by the chemical adhesion between the involving materials is responsible for the bond strength. Debonding process starts soon after the linear branch where a loss of adhesion and stiffness is observed close to F_{max}. The second phase (post-peak) is characterized by a markedly non-linear bond behaviour. Immediately after the F_{max} has been reached, a downward curve branch with a significant slope is observed, followed by a softer slope in more advanced stages. This last stage is mainly governed by friction between the involved materials.

The bond response observed in the F-s_l curves is directly related to the bond mechanisms and consequent failure modes. Three different failure modes were observed (Figure 3): (i) debonding failure at the GFRP/concrete interface + total failure of GFRP ribs (TF), (ii) debonding failure at the GFRP/concrete interface + partial failure of GFRP ribs (PF) and (iii) debonding failure at the GFRP/concrete interface (D). The latter failure mode was the most frequently observed. However, in some tests (e.g. Ø8_Lb5Ø_TW_3; Ø8_Lb10Ø_TW_1,2,3; Ø12_Lb5Ø_TW_2,3), probably due to better mechanical properties of the concrete and consequently better bond conditions, the resisting mechanisms involved the frictional component and also the mechanical resistance of the GFRP ribs. In the F-s_l curves corresponding to these specimens (Figure 2), the post-peak branch has a low slope and, in some cases, there is an increase in the pullout force with the progressive increase of the loaded end slip. The later behaviour may be related to the additional friction and interlocking caused by the ribs that were destroyed.

Figure 4 shows the influence of studied parameters, mainly the GFRP diameter, anchorage length and water type on the bond behaviour. Before proceeding to the discussion of these results, it is important to highlight that F_r/F_{max} ratio (see Table 4) was strongly influenced by the failure mode observed. On average, when total failure of GFRP ribs was observed, F_r/F_{max} ratio increased from 23% to 102% (Figure 4(e)). Regarding the efficiency of the reinforcement system (F_{max}/F_{ult} ratio), in the best case, only 51% of GFRP rod tensile strength was attained (series Ø12_Lb10Ø_TW).

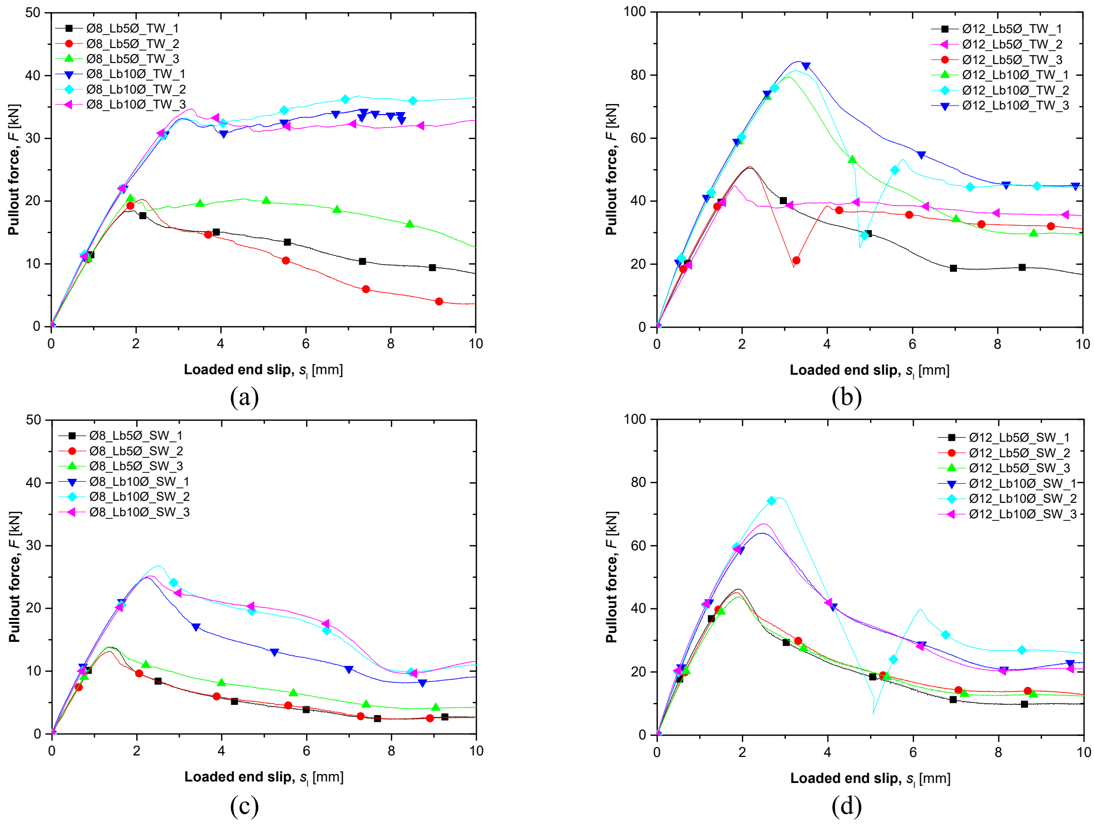


Figure 2 – Pullout force versus loaded end slip curves: (a) Ø8_TW; (b) Ø12_TW; (c) Ø8_SW; (d) Ø12_SW.

<u>Influence of the GFRP diameter</u>

Regarding the GFRP diameter, in spite of the GFRP cross section area (or the external surface in contact with concrete) of the rod Ø12 being 125% larger than the one of rod Ø8, it is found that F_{max} and τ_{max} has increased about 172% and 82%, respectively, when Ø12 was used instead of Ø8 (Figure 4(a) and Figure 4(c)). Thus, it can be concluded that the bond strength tends to increase with the increase of the rod diameter (at least from Ø8 to Ø12). Similar trend was also observed by Mazaheripour et al. (2013) and can be justified by the fact that Ø12 rods show larger ribs, thus promoting better bond conditions than rods Ø8. Consequently, higher values were obtained for the s_{lmax} and s_{fmax} (Table 4). In terms of G_f, a considerable increase was observed (on average about 141%) when Ø12 was used instead of Ø8 (Figure 4(f)).

<u>Influence of the anchorage length</u>

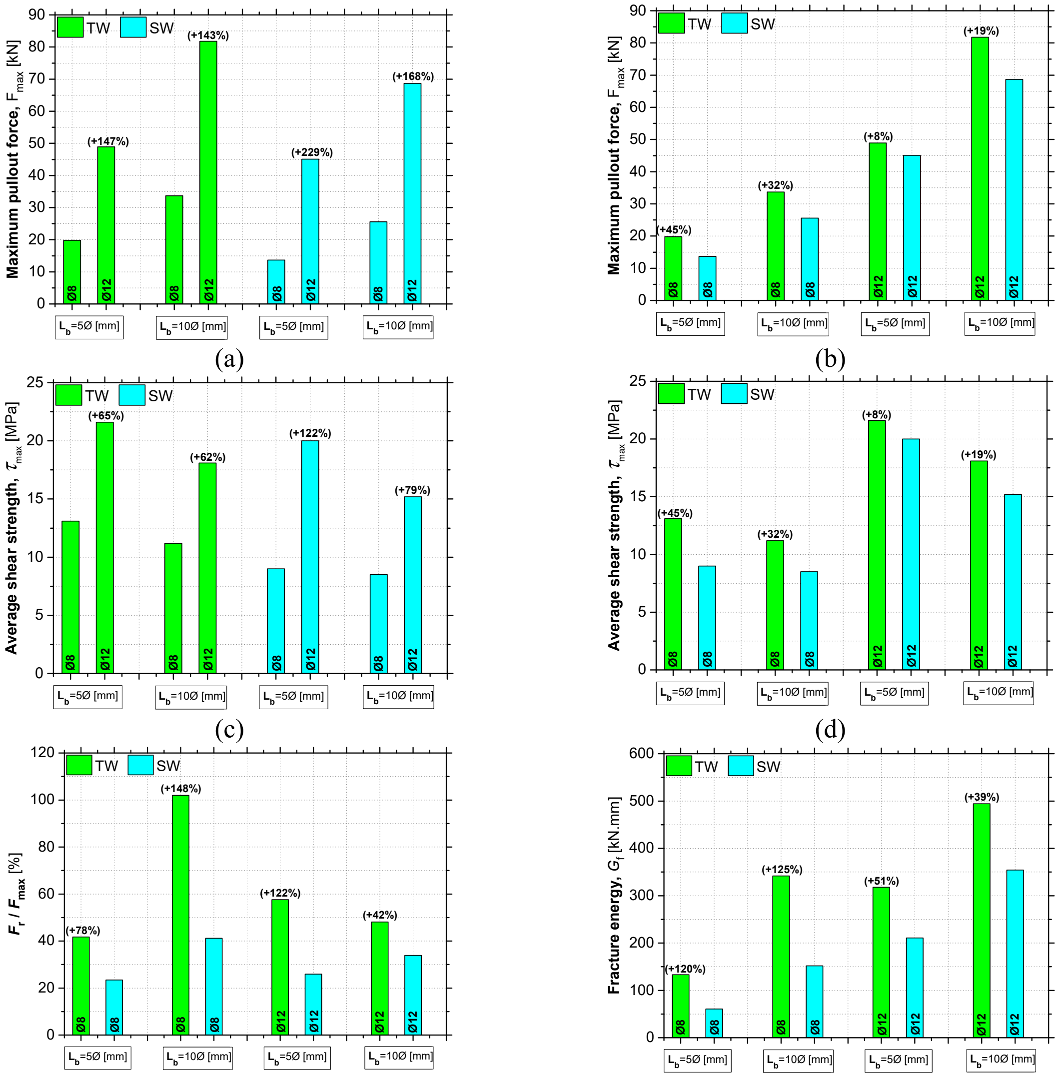
As expected, results demonstrated that by increasing L_b the bond strength has increased, since the adopted lengths are relatively small (lower than effective anchorage length). On average, it is found that F_{max} has increased about 69% when L_b=10Ø was used instead of L_b=5Ø. On the other hand, by increasing L_b, a larger contact surface between reinforcing material and concrete was mobilized and consequently lower τ_{max} values were obtained, due to the non-linear distribution of bond stresses along the anchorage length. According to the results, it is found that the τ_{max} has increased about 19% when a L_b=5Ø was adopted instead of L_b=10Ø. Furthermore, s_{lmax} also increased with L_b. In terms of G_f, a considerable increase was observed (on average about 108%) when L_b=10Ø was used instead of L_b=5Ø (Figure 4(f)).

<u>Influence of the water type</u>

In general, the analysis of results suggests that the use of TW provided higher bond strength, compared with the use of SW in concrete mixture. On an average, the use of TW instead of SW provided an increase of 26% on the F_{max} and τ_{max} (Figure 4(b) and Figure 4(d), respectively). This can be explained by the presence of mineral, biological and chemical components on the SW, which may have negative effects on the concrete mechanical properties. Similar observations had been made in the concrete characterization tests at 28 days of age which means that the bond behaviour between GFRP and concrete is influenced by the concrete mechanical strength. Regarding F_r/F_{max} ratio, an increase was verified (on average about 98%) when TW was used instead of SW (Figure 4(e)). In terms of G_f, an increase was observed (on average about 84%) when TW was used instead of SW (Figure 4(f)). However, in general it can be considered that the use of SW in the concrete mixture had a minimal and no severe effects on the interface behaviour between GFRP and concrete.

(a) (b) (c)

Figure 3 – Failure modes: (a) TF - debonding failure + total failure of GFRP ribs; (b) PF - debonding failure + partial failure of GFRP ribs; (c) D - debonding failure.



(a) (b) (c) (d) (e) (f)

Figure 4: Bond behaviour characterization: influence of GFRP rod diameter, anchorage length and water type on the maximum pullout force (a-b), the average shear strength (c-d), F_r/F_{max} (e) and fracture energy (f).

CONCLUSIONS

An ongoing research work intends to appraise the sustainability of RC structures in marine environment when using SW in concrete combined with the replacement of conventional steel reinforcement by GFRP rods. An experimental program was carried out in two phases: (i) the development of a concrete mixture (including SW) of high strength, including characterization tests at fresh and hardened state and (ii) assessment of bond behaviour between concrete and GFRP rods through direct pullout tests. In both phases the effect of the use of SW instead TW in the concrete mixture was studied. By carrying out pullout tests the influence of parameters such as GFRP rod diameter and anchorage length were also assessed.

From concrete characterization tests it was concluded that the (i) the SW provided a higher cohesion, viscosity and compactness to the fresh concrete. Results have indicated also that SW may have reduced the concrete setting time and led to a faster development of its mechanical properties; (ii) compression tests performed at 28 days of age showed that the concrete which included TW presented a higher value of compressive strength (≈+15%) and modulus of elasticity (≈+7%).

From the direct pullout test results, the following conclusions can be highlighted: (i) three different failure modes were observed, mainly debonding failure with total, partial or without failure of GFRP ribs; (ii) the larger GFRP rod diameter provided the higher values of F_{max} and τ_{max}. Additionally, higher values of s_l and G_f were also obtained; (iii) the longer L_b provided an increase in F_{max}. On the other hand, by increasing the anchorage length, a larger contact surface between GFRP and concrete was mobilized and consequently lower τ_{max} were obtained, due to the non-linear distribution of the bond stresses along the anchorage length. Additionally, higher values of s_l and G_f were obtained; (iv) The use of SW instead of TW on the concrete mixture had influence on the interface behaviour between GFRP and concrete. In the specimens where SW was included, lower F_{max} and τ_{max} values were obtained. These reductions are directly related to the observed reductions in the concrete mechanical strength at 28 days of age when SW was used. Nevertheless, it can be concluded that the use of SW had no severe effects on the bond behaviour at 28 days after casting.

REFERENCES

Antonov, J.I., Locarnini, R.A., Boyer, T.P., Mishonov, A.V., & Garcia, H.E. (2006). “World Ocean Atlas 2005, Volume 2: Salinity” S. *Levitus, Ed. NOAA Atlas NESDIS 62, U.S. Government Printing Office, Washington, D.C.,* 182 pp.

Barris, C., Torres, L., Vilanova, I., Miàs, C., & Llorens, M. (2017). “Experimental study on crack width and crack spacing for Glass-FRP reinforced concrete beams”, *Engineering Structures,* 131, 231-242.

Dong, Z., Wu, G., Xu, B., Wang, X., & Taerwe, L. (2016). “Bond durability of BFRP bars embedded in concrete under seawater conditions and the long-term bond strength prediction”, *Materials & Design,* 92, 552-562.

Etxeberria, M., Gonzalez-Corominas, A., & Pardo, P. (2016). “Influence of seawater and blast furnace cement employment on recycled aggregate concretes’ properties”, *Construction and Building Materials,* 115, 496-505.

Freitas, N. E. D. (2017). “Sustentabilidade de Estruturas de Betão em Ambiente Marítimo com Recurso a FRP”, *Master Thesis*, University of Minho.

Goldston, M., Remennikov, A., & Sheikh, M. N. (2017). “Flexural behaviour of GFRP reinforced high strength and ultra high strength concrete beams”, *Construction and Building Materials,* 131, 606-617.

Li, Y. L., Zhao, X. L., Singh, R. K. R., & Al-Saadi, S. (2016). “Experimental study on seawater and sea sand concrete filled GFRP and stainless steel tubular stub columns”, *Thin-Walled Structures,* 106, 390-406.

Mazaheripour, H., Barros, J. A., Sena-Cruz, J., Pepe, M., & Martinelli, E. (2013). “Experimental study on bond performance of GFRP bars in self-compacting steel fiber reinforced concrete”, *Composite Structures,* 95, 202-212.

Pereira, J.E.M., (2016). “Estruturas de Betão Reforçadas com Materiais Compósitos em Ambiente Marítimo e Concebidas com Água do Mar”, *Master Thesis*, University of Minho.

Pradelle, S., Thiéry, M., & Baroghel-Bouny, V. (2017). “Sensitivity analysis of chloride ingress models: Case of concretes immersed in seawater”, *Construction and Building Materials,* 136, 44-56.

Ragab, A. M., Elgammal, M. A., Hodhod, O. A., & Ahmed, T. E. (2016). “Evaluation of field concrete deterioration under real conditions of seawater attack”, *Construction and Building Materials,* 119, 130-144.

Xiao, J., Qiang, C., Nanni, A., & Zhang, K. (2017). “Use of sea-sand and seawater in concrete construction: Current status and future opportunities”, *Construction and Building Materials,* 155, 1101-1111.