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Effects of harsh environmental exposures on the bond capacity between concrete and GFRP reinforcing bars

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Abstract. This paper demonstrates an experimental study to evaluate the effects of environmental exposures on the bond between ribbed Glass Fiber Reinforced Polymer (GFRP) reinforcing bars and concrete. The equation recommended by ACI 440-1R-06, for the bond stress,was evaluated in this study. A total of 16 pullout samples, 12with GFRP bars and 4with steel bars, were exposed to two different harsh environments for different periods of time. The exposed harsh environments included direct sun exposure and cyclic splash zone sea water. The variation in the shear (bond) strengths before and after exposure was considered as a measure of the durability of the bond between GFRP bars and concrete.Experimental results showed there is no significant difference of the bond strength between 60 and 90 days of exposures.It also showed that the empirical equation of the bond stress calculated by ACI 440-IR-06 is very conservative.

Keywords: bond; GFRP; pullout; shear; exposure; sea water

1. Introduction

Extensive research has been conducted in the search of an alternative to the steel material that resists corrosion under different environmental exposures in the long run. Glass Fiber Reinforced Polymer (GFRP) rebar was introduced as an alternative to substitute steel. GFRP is well known forits anti-corrosion behavior and its high strength to weight ratio. It can be used in places where severe environment, which can cause steel corrosion, is introduced. These harsh environments include marine environment structures, underground tunnels and bridges where most girders are exposed to salt and water evaporation. However, bonding behavior of GFRP bars needs further investigation due to the limited amount of research done in this area. Several investigations have been carried out to determine GFRP bars bonding durability under certain environmental conditions. Binmokrane and Cousin (2005) investigated the bond between GFRP bars and the concrete by conducting microscopic and physicochemical analysis and tests on cylindrical core samples in order to observe the effect of degradation and aging. It was pointed out that though alkaline ions are available in FRP materials, hydrolysis reactions do not occur and therefore no acidic formation was found. Under the X-ray analysis of GFRP, concrete structure environment

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that is close to the GFRP is not affected since reactions do not occur due to any diffusion from GFRP bars.

Tang *et al*. (2005) studied the bond performance of GFRP bars in polystyrene aggregate concrete. Normal concrete was used and four combinations of polystyrene aggregates were added to the mix by replacing 20, 40, 60, and 80% of the normal aggregate with an equal volume of the polystyrene aggregates. Three types of GFRP bars were investigated; smooth and circular, smooth and elliptical, and sand-coated GFRP bars. Two failure modes were noticed, the first is concrete splitting in tension, and the second was bar pullout failure. All of the specimens with sand-coated GFRP bars failed due to concrete tensile splitting. Some of these specimens had longitudinal cracks because of the high concrete density and strength. Also, it was noticed that the average bond strength was the highest in the specimens with sand-coated GFRP bars and was more than the average strength of mild steel bond strength. On the other hand, the other two types of GFRP, had lower bond strength when compared to the mild steel. Specimens with shorter embedment length had higher bond strength because of the reduced perimeter area. This was due to the pullout force increase when the embedment length increases.

Masmoudi *et al*. (2011) performed eighty pullout tests for specimens at a temperature ranging from 20 to 80^{o}C in a dry environment to evaluate the performance of the bond between the GFRP rebar and normal concrete. The length of the GFRP bars was 500mm and the embedment length was 5d_b. It was noticed that up to 60^{o}C there wasn't any significant reduction in the bond strength between the GFRP bars and the concrete. The reduction was around 2% and 4% for the 8mm and 16mm specimens respectively. However, when the temperature was 80^{o}C, the reduction in the bond strength increased to almost 10% and 14% for the 8mm and 16mm specimens, respectively. Also, it was noticed that the bond strength decrease when the diameter increase, this is because of the difference in the contact surface at the interface between the bars and the concrete.

Al-Sallom and Almusallam (2006) studied the effect of different environmental conditions on the creep behavior of GFRP reinforced concrete beams which were under a sustained load equal to 23% of the ultimate strength of the bars. These environmental effects were studied by casting eight concrete beams with dimensions of 100 mm ×100 mm ×2000 mm and a compressive strength of 43 MPa. The first group of beams was the reference group and it was loaded at a temperature-controlled laboratory (24 ± 3C). Then three tanks were fabricated for the other three groups.Each tank was painted with enamel paint for protection and had an electrical heaters and a thermostat to control the temperature of water to about (40 ± 2C). The first tank was for beams continuously exposed to tap water, the second tank was for beams continuously exposed to seawater and the third tank was for beams exposed to cycles of wet/dry seawater. After the test was conducted the mid-span deflection and the strains in the GFRP and concrete beams were measured. It was found that the highest increase were in the third tank where it was exposed to cycles of wet/dry seawater. The increase in the mid-span deflection in this tank was 20%, the increase in the tensile strain was 48%, and the increase in the compressive strain was 82 % all with respect to the reference group.

Mazaheripour *et al*. (2013) investigated the bond performance between two types of GFRP bars and steel fiber reinforced self-compacting concrete (SFRSCC) by performing 36 pullout bending tests. It was found out that the specimens failed by debonding, indicating that the bond length to attain the ultimate tensile strength of the bars is higher than 20 diameter for the two types of GFRP bars when embedded in the adopted SFRSCC. The bond failure was mostly dominant by the shear resistance of GFRP surface layers. However, other specimens where a single splitting crack was formed, a mixed damage configuration in the bar was observed, with scratched ribs on the top surface of the bar and inclusions of cement paste in between the GFRP ribs at the bottom part of the bar. It was also observed that by increasing the concrete cover the post-peak pullout force increased, and consequently the average residual bond stress as well.

Thus from the literature provided above, it can be seen that many researches have been established to study the effect of the temperature on the bond strength, increasing bar diameter (Tighiouart *et al*. 1998, Achillides and Pilakoutas 2004), mode of failure and creep. However, very limited studies have been done to study the effect of cyclic splash zone sea water on GFRP bars that are already embedded in concrete specimens. Also there is no enough information in the literature about the effect of direct sun exposure on GFRP bars. This might be a main concern for contractors and owners, because it is hard to control the storage environment of GFRP bars in any construction site. This study sought responses to such issues through simulating field conditions: immersion of concrete-wrapped GFRP bars in sea salty water and characterizing the short and long-term performance GFRP bars bonding. More specifically, the main objective of this study is to characterize the short and long-term durability of bond between GFRP bars and concrete with pullout tests. Also the equation recommended by ACI 440-1R (ACI 2006) for shear stress calculation will be evaluated using the results of the pullout tested specimens under controlled condition.

2. Experimental program

The main objective of the testing program is to evaluate the performance of GFRP bars embedded in concrete and subjected to different harsh environments. The evaluation will be based on the bonding strength of these specimens after subjecting them to direct sun exposure and cyclic splash zone sea water. Additionally, some specimens were kept in lab controlled conditions. Steel specimens were also introduced to compare between GFRP and steel bond strength. Table 1presents some details about the exposure conditions for the present experimental program.

The labeling system presented in this manuscript is slightly different than the system used in the actual experimental program. In this paper, the cube samples have been labeled for each type of exposures as 1 and 2 depending in their exposure period. The label number 1 refers to 60 days exposure and number 2 refers to 90 days exposure. For example, samples “Lab1” and “Lab2”refer to pullout samples that were kept in the lab under normal (controlled) condition for 60 days and 90 days, respectively. Similarly the terms “Sun” and “Water” used in the labeling system refer to pullout samples which were exposed to direct sun and salty sea water, respectively. On the other hand, the two steel pullout samples were labeled as “Steel 1” and “Steel 2” which were kept under normal condition in the lab for 60 days and 90 days, respectively. Two specimens for each case were considered and the average results were reported in this study.

2.1 Concrete mixture design

High strength concrete was used and theconcrete mixture proportioning is presented in Table 2. Standard concrete cubes 150 × 150 × 150 mm were cast and cured at room temperature (22^{o}C). The pull-out specimens and the standard concrete cubes were cast in two layers and compacted using a vibrator. The compressive strength was 54 ± 2MPa after 28 days of curing at water curing tank as it can be seen in Table 3.

2.2 GFRP Bars

The ribbed Glass Fiber Reinforced Polymer bars used in pull-out specimens were manufactured by using fiber composites and were combined with synthetic resin to achieve improved properties, such as higher strength and elevated modulus of elasticity (Schock 2006). The tensile properties of the bars used in this study are presented in Table 4. These properties were based on experimental tests conducted by Pultron Composites laboratories that manufactured these GFRP bars. The diameter for both GFRP and steel bars was 13 mm.

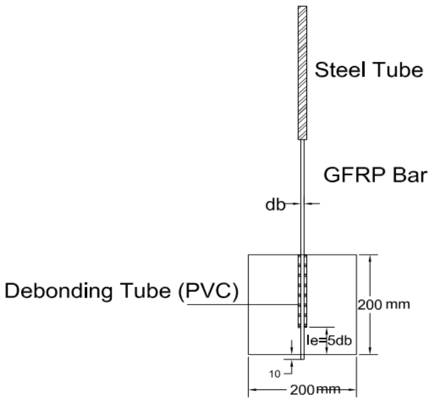


Fig. 1 Geometric description of the pullout sample

Table 1 Exposure program

Specimen designated name	Type of exposure/ Environment	Exposure duration (Days)	Contact length*
Lab 1	Controlled (23°C)	60	$5d_b$
Lab 2	Controlled (23°C)	90	$5d_b$
Sun 1	Direst sun exposure	60	$5d_b$
Sun 2	Direct sun exposure	90	$5d_b$
Water 1	Salty sea water	60	$5d_b$
Water 2	Salty sea water	90	$5d_b$
Steel 1	Controlled (23°C)	60	$5d_b$
Steel 2	Controlled (23°C)	90	$5d_b$

Table 2 Mixture proportion and concrete characteristics

Mix No.	C16DNO	Material	Kg/m^3
Strength class	C 50	Cement	440
W/C	0.38	GGBS	0
Air content	1.5%	MS	0
Cement type	OPC	Water	167
Density	2500 kg/m^3	CR. washed sand (0/5 mm)	630
Weight	25.95 kg	Red dune sand (0/0.6 mm)	230
Slump	140 mm	CR. sand (0/5 mm)	0
Temp.	23°C	CR. aggregate (10/20 mm)	670
Volume	0.01 m^3	CR. aggregate (5/10 mm)	350

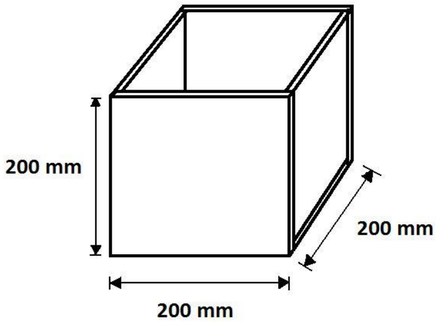
Table 3 Concrete compressive strength after 28 days curing

	Cube dimension	Compressive strength
	mm	MPa
NO.1	150 × 150 × 150	54.6
NO.2	150 × 150 × 150	53.8
NO.3	150 × 150 x 150	54.9

Table 4 GFRP reinforcing bar characteristics

Material property	Value	Standard
Tensile strength	800 MPa	ASTM D3916
Strain at break	0.024	ASTM D3916
Modulus of elasticity	54.5 GPa	ASTM D638
Shear strength	230 MPa-520 MPa	ASTM B769-94
Compressive strength	460 MPa 690 MPa	ASTM D695
Moisture absorption	500 MPa 0.024%	BS2782 pt 4, method 430/ ISO 62-1980
Thermal conductivity	0.25w/mk^{-1}	ASTM C117
Electrical strength	5-40kV/mm	DIN 53 481
Volume resistivity	10^{10}Ω.m	DIN 53 482
Density	1.9-2.1g/cm^3	

(a)



(b)

(c)

(d)

Fig. 2 Pullout test samples preparations

2.3 Specimen preparation

Pullout tests, beam tests and splice tests are most commonly used to evaluate the bond behavior (Zhou *et al*. 2011). As an economical and simple solution for the evaluation of bonding performance, pullout test is widely implemented. The splitting of concrete during pull-out testing can be avoided by providing relative large volume of concrete surrounding the bar and increasing the embedment length of the bar. A sketch of the pullout specimen is shown in Fig. 1.

The pullout test specimens and the cubes sizes of 200 mm ×200 mm × 200 mm are shown in Fig. 2. The specimens were fabricated by positioning the bars vertically through a wood alignment guiding frame. Contact between the concrete and the bars along the debonded length was broken using a soft plastic tube. The concrete specimens, with embedded GFRP /steel bars were removed fromthe molds one day after casting, and were then subjected to different environmental conditions as it has been described in the earlier section.

Special process was conducted in order to protect the cube and the embedded GFRP bar. The top surface of each cube was filled with epoxy paint, Concressive 1450i which is a high performance styrene free epoxy crylate based fixing compound, for water proofing (Fig. 2c). Then the GFRP bar's bottom length, where the embedded steel sleeve appears, was surrounded by silicon to prevent the water or any other chemical to penetrate inside the steel sleeve.

GFRP bars cannot directly resist the applied pressure which will cause crushing, thus the best solution was to use steel anchors, as recommended by ASTM (D7205/D7205M-06). Steel anchors (Fig. 2d) were used to make the rebar resist large pressure without crushing when gripped by the universal testing machine (UTM). The ASTM standard specifies the anchor's length and diameter required for different rebar's sizes. For the 13 mm GFRP bar used in this study, the recommended size of the steel anchor is 380 mm length and 42 mm diameter. On the top of the anchor, there is steel threaded plug for attachment to load head and to ensure that the steel anchor can receive large pressure from the testing machine without deflecting or failing. The bonding between the steel anchor and the GFRP rebar was provided by applying a mixture of strong epoxy with its hardener. Concressive 1450i provided a very strong bond that enforced the failure to occur in the bond between the GFRP rebar and the concrete cube. Applying the epoxy, between the steel anchor cylinder and the GFRP rebar, was done by using threaded plug and some wooden forms. The wooden forms were used to ensure that the location of GFRP rebar is in the center of the steel gripping anchor.

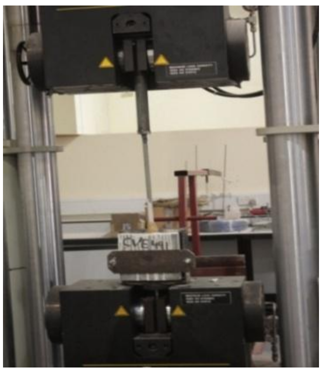


Fig. 3 Experimental pullout test setup using a UTM with 1200 kN load capacity

2.4 Pullout test setup

The test was carried out using UTM machine at a rate of 2.0 mm/min. For each pullout test, the specimen was mounted on the press with steel anchor gripped by the machine’s wedges (Fig. 3). A steel cage was manufactured to maintain the concrete in a stable position and prevent it from moving upward while pulling the GFRP bar. As it can be seen from Fig. 3, the size of the steel cage was chosen to be consistent with the size of the concrete cube 220 mm by 220 mm. The same steps were followed for the two steel pullout specimens except that no anchors were used for the steel bars.

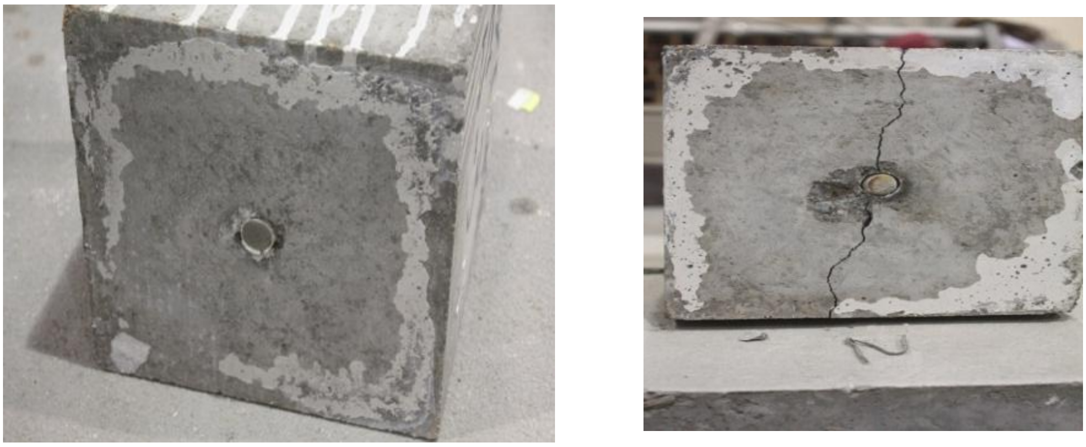
3. Results and discussion

3.1 Failure mode

The development (contact) length between the concrete and the GFRP bar provided for all of the cubes in this paper was taken as $5d_b$, as specified by the ACI 440.3R-04 B3, which is 65 mmfor the present study. A length of 10 mm of the bar was kept outside of the cube from the bottom to observe whether slippage is the govern failure mode of the pullout test. As it can be seen from Figs. 4 through 6, the most common failure mode of all cube samples is slippage of GFRP bars from the cubes. Pure slippage was observed for samples “Lab 1”and “Lab 2” (see Fig. 4) and for sample “Water 1” (see Fig. 5a). However, the slippage for “Sun 1” sample was accompanied with tensile failure in the concrete (Fig. 6a). The 90 days exposed samples “Sun 2” and “Water 2” have failed in slippage but the ribs/coating of GFRP bars remained in its place. This shows that these bars had a weak connection between the ribs and the bar itself which might have happened due to the water/ sun exposure or due to the manufacturer defects. Finally one of the steel samples “Steel 2”suffered some necking (yielding) while slippage was taking place (Fig. 7). This result is expected since the load has gone up to 119 kN which means that the stress in the bar has exceeded its yielding capacity of 460MPa. While testing “Steel 1’ sample, the steel cage has suffered flexure failure which affected the result of the sample.

(a) Lab 1 (b) Lab 2

Fig. 4 Failure modes of the two pullout samples stored inside the lab



(a) Sun1 (b) Sun 2

Fig. 5 Failure modes of the two pullout samples under direct sun exposure

(a) Water 1 (b) Water 2

Fig. 6 Failure modes of the two pullout samples under salty sea water exposure

Fig. 7 Failure modes of the two steel pullout samples stored inside the lab

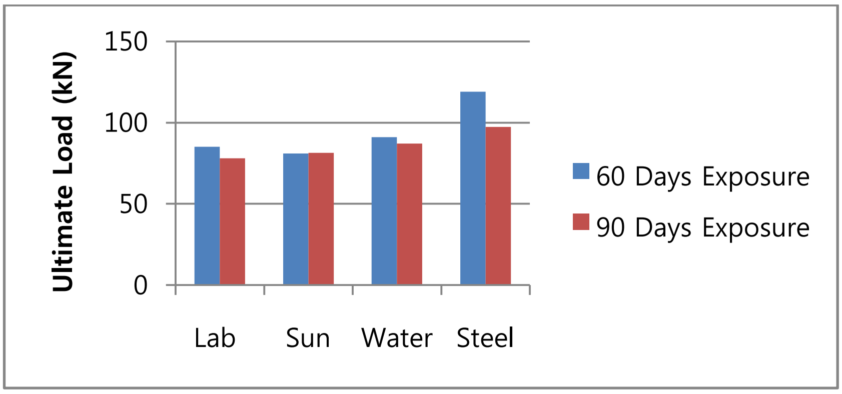


Fig. 8 Bar charts showing comparisons between all pullout samples

Table 5 Comparison of bond stresses between experimental and coderesults

Sample designation	Load (Exp.) (kN)	Shear stress Exp. (MPa)	Shear stress (ACI Code) (MPa)	Type of failure
Lab 1	85.2	32.1	15.4	Slippage
Lab 2	78.0	29.4	15.4	Slippage
Sun 1	81.0	30.5	15.4	Concrete tensile failure then slippage
Sun 2	81.4	30.7	15.4	Separation of coating (ribs) then slippage
Water 1	91.0	34.3	15..4	Slippage
Water 2	87.1	32.8	15.4	Separation of coating (ribs) then slippage
Steel 1	97.3	36.7	-	Necking then slippage
Steel 2	119	44.8	-	Necking then slippage

3.2 Comparison of different exposure periods

It must be noted that the exposure took place after curing all the cube samples, with the bars embedded in them, for 28 days. The bar chart presented in Fig. 8 illustrates the variation in the ultimate load at which the slippage took place in all samples. It can be clearly shown that no significant differences between the ultimate load after 60 and 90 days exposure except for the steel bar samples. The steel bar variation happened due to the flexural failure of the steel cage that was designed to hold the sample, thus the difference that has occurred is rational.

3.3 Comparison of experimental bond (shear) stress with ACI code equation

The experimental shear (bond) stress of each sample has been calculated by dividing the ultimate load, presented in Table 4, by the embedded contact area $5\pi d_b^2$between the concrete and the GFRP bar. Wambeke and Shield (2006) performed bond tests and collected many data to come up with a linear regression equation for the normalized average bond stress versus the normalized cover and embedment length as given by Eq. 1 below

$$\frac{u}{0.083\sqrt{f_c'}} = 4.0 + 0.3\frac{C}{d_b} + 100\frac{d_b}{l_e} \quad (1)$$

The above equation is also recommended to be used by the ACI 440-1R-06 code, where u is the shear stress, c is the lesser of the cover to the center of the bar or one-half of the center-on-center spacing of the bars being developed, d_b is the bar diameter, and le is length of FRP bar embedded in the concrete. In this study, Eq. 1 is used to estimate the shear (bond) stress that will bare a certain development length. IT is obvious that all the 6 GFRP pullout samples have the same theoretical shear stress as given by the fourth column in Table 5. This is because the exposure effect was not accounted for when developing the above equation. It is also very clear that equation recommended by the code provides a very conservative estimation for the slipping stress. The shear stress that the GFRP cube bare from its bond is approximately twice of that estimated by the code equation. Moreover, the steel bond with the surrounding concrete is 28% more than GFRP bond.

4. Conclusions

A total of 8 different pullout tests were conducted in this paper to study the bond behavior between GFRP reinforcing bars and relatively high strength concrete. The main aim of this study was to investigate the effect of harsh environment on the bond stresses developed along the GFRP bars when embedded inside concrete. The pullout samples were tested after direct exposure to sun and also to sea water for two periods of 60 days and 90 days. There was no significant difference in bond stress between 60 and 90 days of exposures both under sun and cyclic splash zone effects.The predominant mode of failure for the pullout testes was a pure slippage, accompanied in one case with a tensile concrete failure at the bottom region of the concrete cube.The experimental shear stresses were also compared with theoretical values recommended by the ACI 440-IR-06. It was concluded that the empirical equations used to calculate the development length by ACI 440-IR-06 are very conservative compared to experimental results.

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