Enhancing the Bond Durability of Basalt Fiber Reinforced Polymer Bars Using Basalt-Macro Fiber Reinforced Concrete

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Abstract

This paper presents a study about the bond durability of basalt fiber reinforced polymers (BFRP) bars embedded in concrete incorporating basalt macro fibers (BMF) when conditioned in harsh saline environment at 60 °C. A total of 24 pullout specimens were tested to investigate the influence of concrete type (plain concrete and fiber reinforced concrete) and duration of conditioning (30, 60 and 90 days). The basalt-macro fiber reinforced concrete (FRC) incorporated BMF at 0.5% fiber volume fraction. The BFRP bars used had helically wrapped surface treatment. Moreover, the bond durability was assessed based on bond-slip behaviour, bond degradation, and service life predictions of bond strength retentions after 50 years of service life. The experimental results revealed that BFRP bars embedded in basalt macro FRC showed higher bond stiffness compared to those embedded in plain concrete. Additionally, BFRP bars embedded in basalt macro FRC showed slower bond degradation than their counterparts embedded in plain concrete. Finally, FRC increased the bond strength retentions of BFRP bars based on 50 years' service life predictions when compared to plain concrete.

Keywords: BFRP bars; Bond strength; Bond durability; Basalt-Macro FRC; Saline environment

1 Introduction

BFRP bars are becoming promising alternatives to the conventional glass fiber reinforced polymers (GFRP) bars because of their lower cost and similar mechanical properties (Attia et al., 2020; ElSafty et al., 2014). In general, basalt fibers possess larger failure strains and enhanced resistance to chemical attacks compared to carbon fibers and glass fibers respectively (Sim & Park, 2005)). Fiber reinforced polymer (FRP) bars may have different bonding mechanism compared to conventional steel reinforcements because of their anisotropic and linear elastic behaviours in addition to having wide variety of surface treatments. Numerous studies examined the bonding behaviour of FRP bars to concrete (El Refai et al., 2015; Yan & Lin, 2017).

Furthermore, exposing FRP reinforcements to high temperatures, environments of high humidity, chemical attacks, or any combination of these environments can cause strength reductions of FRP bars. These reductions can in turn result in negative alterations to the bonding behaviour of FRP reinforcements throughout their life use (El Refai et al., 2015). Few studies have been implemented on the durability of BFRP bars' bonding mechanism unlike the GFRP bars' bonding durability which have been examined thoroughly in the literature (D'Antino *et al*., 2018; Yan & Lin, 2017). Hassan et al., (2016) examined the effect of high alkaline environment at high temperature on the BFRP bars' bond durability. The variations in the BFRP bars' bond strength after 6 months of exposure were insignificant when compared to the specimens that were unconditioned. In the contrary, 25 % reduction in BFRP bars' ultimate bond stress was reported by (Altalmas et al.,(2015) when subjected to saline and alkaline conditions for a total of 90 days.

Besides, few research studies examined the influence of FRC on the FRP bars' bond durability. Majority of these investigations have been done on the conventional GFRP reinforcements. Commonly, using FRC mixes improved the FRP reinforcements' bond stress (Liu et al., (2017; Yan & Lin, 2017)). A research study about the influence of structural fibers on bond durability of GFRP reinforcements subjected to harsh seawater conditions was performed by Yan et al., (2017). The study indicated enhanced GFRP reinforcements' bond durability when FRC is used. Similarly Belarbi & Wang (2012) reported higher bond stress retentions of GFRP reinforcements embedded in FRC than plain concrete subjected to extreme temperatures, seawater conditions, as well as cycles of freeze and thaw.

Based on the aforementioned discussion and since the FRP bars' bond strength is what governs the structural capacity as well as the serviceability of FRP reinforced concrete structures, therefore the bond durability of FRP bars to concrete is critical in determining the durability performance of structures utilizing FRP reinforcements Davalos et al., (2008)). It is noteworthy to point out that the durability of BFRP bars' bond in FRC is lacking in the literature. Hence, this study provides experimental as well as analytical examinations on the BFRP bars bond performance and durability when surrounded by FRC while subjected to seawater conditions at high temperature for different conditioning durations.

2 Experimental Program

2.1 Preparation of Pull-Out Specimens

24 specimens for pullout testing were prepared to examine the influence of exposure duration and type of concrete on the BFRP bars' bond strength durability in seawater conditions. The tested specimens were divided into three groups. The 1st group denotes the unexposed specimens, and the remaining two groups correspond to the exposed counterparts. The labelling of the specimens was done in the subsequent order: concrete type, duration of conditioning, exposure temperature, and number of the specimen. For example, 0.5%BF-30-60-2 denotes the second identical pullout specimen of FRC with volume fraction at 0.5% conditioned for 30 days under 60 °C. The specimens of pullout testing were prepared in accordance with ASTM D7913 (2014) and a sample with its details is shown in Fig.1. Moreover, a total of 24 compressive strength cylinders were prepared according to ASTM C39 (2020) to track the compressive strength throughout the conditioning.

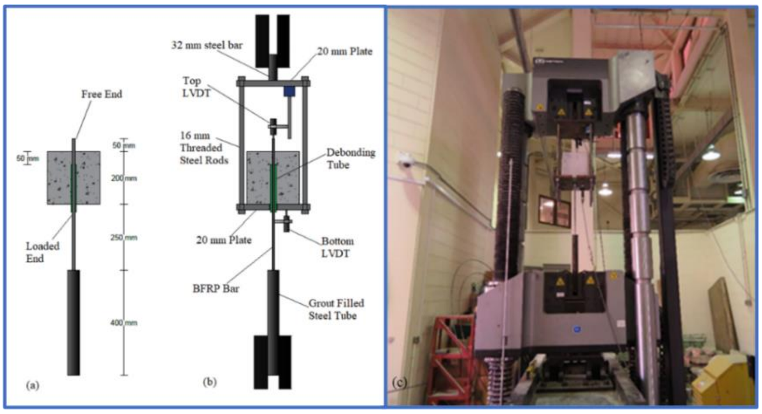

Fig. 1: (a) Details of Specimens for Pullout Test; (b) Details of Test Setup; (c) Test Setup Photo

2.2 Conditioning Environment

All the specimens were cured for 28 days. Control specimens were under lab conditions until the end of the conditioning, whereas other specimens were conditioned in saline environment at 3.9% NaCl concentration inside temperature-controlled tank to simulate the seawater of the gulf region. The temperature of the simulated seawater was chosen to be 60 °C to simulate accelerated conditions. Furthermore, the conditioning durations of this durability test were chosen to be 30, 60, and 90 days.

2.3 Materials

The BFRP bars and BMF used in the study are depicted in Fig. 2. Table 1 depicts the properties of the used BMFs as per the manufacturer's data sheet. Subsequently, Table 2 depicts the concrete mix design used, which was selected to achieve a 28 MPa target compressive strength. The bars used in this study were BFRP bars with surface treatment of helical wraps labelled as HWBFRP bars as depicted in Fig. 2(a). The nominal diameter of the used HWBFRP bars was 10mm. The polymeric resin used for manufacturing the HWBFRP bars was vinyl ester. The bars used had a modulus of elasticity of 44 GPa and a 1100 MPa of tensile strength with a density of 1900 kg/m^3.

Table 1: BMF Properties

Type	Diameter (mm)	Length (mm)	Aspect Ratio	Density (g/cm^3)	Tensile Strength (MPa)
BMF	0.72	43	59	2.1	900

Table 2: Concrete Mix Designs

Concrete Mix Type	Fiber Type	Water (kg/m^3)	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	Sand (kg/m^3)	Fiber Volume Fraction (%)	Superplasticizer (kg/m^3)
Plain concrete	-	204	350	1082	714	0	0
0.5%-BMF	BMF	204	350	1082	714	0.5	0.27

Fig. 2: (a) HWBFRP Bars; (b) BMF

2.4 Test Setup

To conduct the pullout test, a 1500 kN universal testing machine (UTM) was used. To measure the loaded and free end slippages, two linear variable displacement transducers (LVDTs) were used. The loading rate of the pullout specimens was 1.2 mm/min as per ASTM D7913 (2014). Fig.1(b) depicts the test setup details.

The following equation was used to obtain the average bond strength:

$$\tau = \frac{P}{\pi d_b L_d} \quad (1)$$

Where τ is the bond stress, d_b is the diameter of the bar, P is the ultimate load, and L_d is the embedded length of the bar inside the concrete.

3 Test Results and Discussion

3.1 Bond-Slip Response

Fig. 3 shows the response of the bond slip for control pullout specimens as well as conditioned specimens being immersed for 90 days. In general, the bond behaviour of pullout specimens consisted of an ascending branch till the point where the surrounding concrete starts to crack causing a reduction in the rate of increase in bond stress associated with increase in slippage. This continues until the ultimate stress is attained followed by descending branch where a gradual decay occurs in the bond stress caused by the wedging action of BFRP bar's indentation on the concrete surrounding it.

As can be inferred from Table 3, The usage of FRC increased the HWBFRP bars bond strength for control and conditioned specimens. This increase can be ascribed to the fibers crack effect of bridging throughout the induced cracks in the surrounding concrete because of the pullout loads. For unconditioned specimens the enhancement of adding 0.5%BF to concrete was insignificant, however it is worth to mention that the bond stiffness of HWBFP bars was significantly improved in FRC by achieving slightly higher bond strength at considerably lower slippage. Such behaviour will limit excessive cracking in reinforced concrete (RC) structures making basalt FRC and HWBFRP system highly recommended for serviceability limit state (SLS) design considerations of FRP RC structures. It is noteworthy to mention that the minimum bond stress obtained for control specimens was 13.1 MPa which is significantly higher than minimum requirement of ACI 440.6 M(2008).

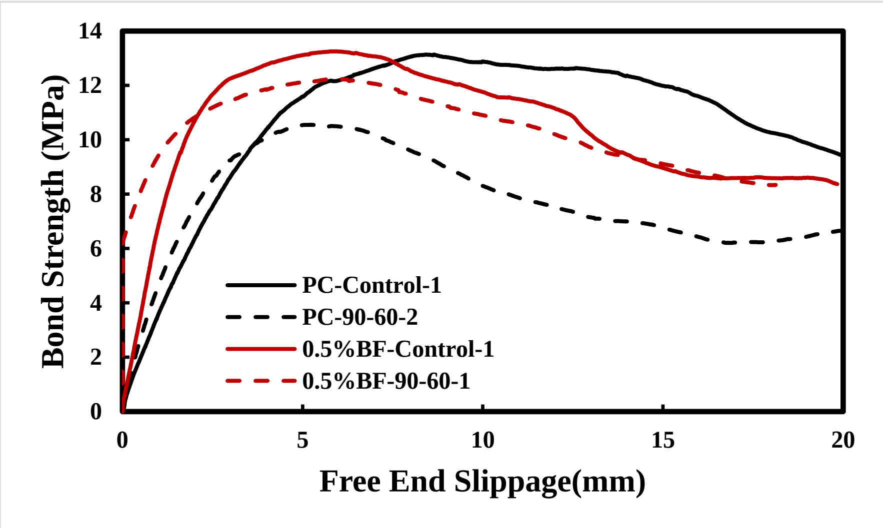

Fig. 3: BFRP Bars Bond-Slip Response

Table 3: Results of Bond Test

Specimen	f'c (MPa)	τ_{max} (MPa)	τ^*_{max} (MPa)	δ_{FE} (mm)	Failure Mode	Retention (%)
Control Specimens at 23 °C						
PC-C-1	32.5	13.14	13.14	8.65	P	100
PC-C-2		11.78		6.21	P	
PC-C-3		14.49		6.44	P	
0.5%BF-C-1	30	13.25	13.27	5.84	P	100

0.5%BF-C-2		12.64		6.18	P	
0.5%BF-C-3		13.91		7.54	P	
Exposed Specimens at 60 °C for 30 days						
PC-30-60-1	29.3	12.14	13.4	6.59	P	102
PC-30-60-2		13.38		7.01	P	
PC-30-60-3		14.69		5.51	P	
0.5%BF-30-60-1	31.2	17.2	15.18	7.76	P	114
0.5%BF-30-60-2		12.32		4.45	P	
0.5%BF-30-60-3		16.02		5.77	P	
Exposed Specimens at 60 °C for 60 days						
PC-60-60-1	34.4	16.34	12.17	3.97	P/R	93
PC-60-60-2		11.65		7.07	P	
PC-60-60-3		8.52		5.49	P	
0.5%BF-60-60-1	33.1	12.28	14.72	9.07	P	111
0.5%BF-60-60-2		16.83		3.37	R	
0.5%BF-60-60-3		15.05		8.2	P	
Exposed Specimens at 60 °C for 90 days						
PC-90-60-1	35.6	11.6	11.77	8.68	P/R	90
PC-90-60-2		10.56		5.2	P	
PC-90-60-3		13.15		4.824	R	
0.5%BF-90-60-1	34.2	12.24	14.03	5.78	P	106
0.5%BF-90-60-2		14.05		4.5	P	
0.5%BF-90-60-3		15.81		4.87	R	

**f'c: The Compressive Strength of Concrete; $\tau_{max:}$ Ultimate Bond Stress; $\tau^*_{max:}$ Average Bond Stress; δ_{FE}: Free End Slippage; P: Pullout Failure; R: Rebar Fracture; P/R: Pullout Followed by Rebar Fracture.

3.2 Bond Degradation

Fig.4 shows the column chart of the average bond stress of all tested specimens. After 90 days of conditioning the decrease in the bond stress of plain concrete was 10 % compared to control specimens, whereas no reduction was noticed for conditioned FRC pullout specimens compared to their control counterparts. These results can be ascribed to the capability of BMF to limit the ingress of chlorides throughout the porous network of the concrete (Mohamed & Al-Hawat, 2016). After 30 days of exposure, all conditioned specimens tended to exhibit bond strength reduction with the increase of conditioning duration. Plain concrete pullout specimens vulnerable for 90 days experienced 12% reduction in comparison with their 30 days conditioned counterparts. On the other hand, 0.5%BF pullout specimens showed a decrease of 8% in comparison with the 30 days conditioned specimens. This degradation in the bond stress along with time can be ascribed to the presence of chloride environment and moisture at high temperature. The presence of chlorides can detrimentally affect the interfacial shear strength between the fibers and their surrounding matrix (Tam at al.(2019)). Furthermore, the differences in the coefficient of thermal expansion between concrete and the used bars can lead to different rates of expansions and contractions causing voids that can be filled with chlorides and thus accelerating the degradation of the bond performance between the bar and the concrete surrounding it (Belarbi & Wang, 2012).

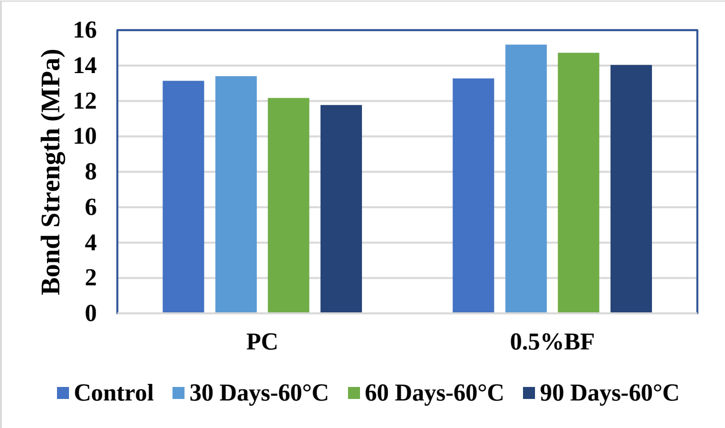

Fig. 4: Bond Degradation of HWBFRP Bars in Plain and FRC Concrete

3.3 Service Life Prediction

The methodology mentioned in the fib Bulletin 40 (2007) can be implemented to predict the bond stress retention after a specified service life. The bond stress of the used bars can be decreased by an environmental factor ,$\eta_{env,}$ mentioned in the following equations:

$$\eta_{env,b} = 1/[(100-R_{10})/100]^{n} \quad (2)$$

$$n = n_{mo} + n_{T} + n_{SL} \quad (3)$$

where R_{10} is the slope of the trend line of degradation fitted in double logarithmic scale. n_{mo},n_{T} and n_{SL} are parameters of humidity, temperature, and required service life respectively. Fig. 5(a) shows the double logarithmic fitting of the bond strength retention values of HWBFRP bars in plain concrete. Whereas, Fig. 5(b) shows the bond retention values of HWBFRP bars in FRC when fitting them in double logarithmic scale. Table 4 shows the obtained bond retention predications based on 50 years' service life. It can be inferred that after 50 years under service, the bond stress retentions of BFRP bars in plain concrete is in the range of 56 to 86% depending on moisture conditions whereas when embedded in 0.5%BF concrete, the retentions varied between 74 to 92%.

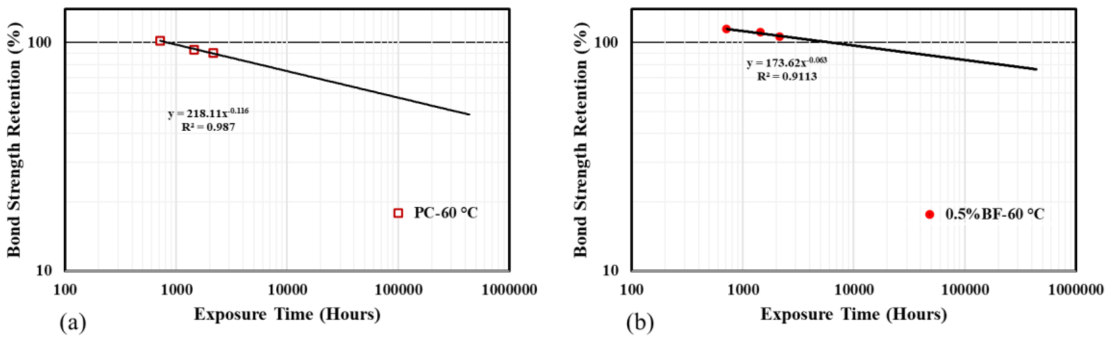

Fig. 4: Double Logarithmic Retention of HWBFRP Bars in (a) Plain Concrete; (b) FRC

Table 4: Bond Strength Service Life Predictions

					Plain Concrete		**Basalt FRC**	
n_{SL}	n_{mo}	MAT (°C)	n_T	n	$\eta_{env,b}$	$1/\eta_{env,b}$(%)	$\eta_{env,b}$	$1/\eta_{env,b}$(%)
2.7 (50 years of service life)	-1 (Dry)	<5	-0.5	1.2	1.16	86	1.08	92
		(5-15)	0	1.7	1.23	81	1.12	90
		(15-25)	0.5	2.2	1.31	76	1.15	87
		(25-35)	1	2.7	1.4	72	1.19	84

	0 (Moist)	<5	-0.5	2.2	1.31	76	1.15	87
		(5-15)	0	2.7	1.4	72	1.19	84
		(15-25)	0.5	3.2	1.48	67	1.23	81
		(25-35)	1	3.7	1.58	63	1.27	79
	1 (Moisture Saturated)	<5	-0.5	3.2	1.48	67	1.23	81
		(5-15)	0	3.7	1.58	63	1.27	79
		(15-25)	0.5	4.2	1.68	60	1.31	76
		(25-35)	1	4.7	1.79	56	1.36	74

4 Conclusion

In conclusion, this paper investigated the effect of concrete type and conditioning duration on the bond durability of HWBFRP bars under extreme seawater conditions. The following conclusions can be outlined:

- Basalt macro FRC significantly improved the bond stiffness of HWBFRP in comparison with plain concrete making the usage of basalt macro fibers recommended for SLS design considerations of FRP RC structures.
- The bond strength at 90 days of exposure for HWBFRP bars in basalt macro FRC was 19% higher than HWBFRP bars surrounded by plain concrete.
- The bond stress retentions throughout the conditioning of HWBFRP bars in plain concrete were 102, 93, and 90% at 30,60,and 90 days respectively, whereas the retentions of the bond stress for their counterparts embedded in basalt macro FRC were 114, 111, and 106% at 30,60,and 90 days respectively indicating slower degradation.
- Based on 50 years' predictions, the retentions of the bond stress for HWBFRP bars in plain concrete were in the range of 56 to 86% depending on moisture conditions, whereas when embedded in basalt macro FRC, the retentions varied between 74 to 92%.

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