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Effect of FRP bar degradation on interface bond with high strength concrete

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ABSTRACT

An experimental investigation is described on the durability performance of FRP bar-concrete interface bond, purposely focused on the surface material degradation of FRP bar by using a concrete mix with high compressive strength. A total of 48 pullout specimens with four different types of FRP bars were cast for bond strength tests. Additional specimens were also cast for concrete compressive strength test, visual inspection of FRP-concrete interface, and scanning electron microscopy analysis to evaluate the environmental effects. Specimens were exposed to the following conditions: tap water maintained either at ambient temperature or 60 °C, and air of thermal cycling from −20 to 60 °C. The environmental conditioning resulted in bond strength reductions of 4–10% for CFRP bars and 0–20% for GFRP bars. The conditioning also increased the free-end slip before the peak bond strength was reached. The degradation of bond was related mainly to the deterioration of FRP bar and less to concrete. The interface bond failure mode and degradation mechanism due to FRP bar damage are characterized.

1. Introduction

Significant efforts and resources have been devoted to condition assessment, rehabilitation and repair of deteriorating infrastructure. The main cause of deterioration of existing reinforced concrete (RC) structures is the corrosion of steel reinforcement. To address this problem, fiber-reinforced polymer (FRP) reinforcing bars are being increasingly used as a favorable alternative, due to advantages such as resistance to corrosion under deicing salts, high strength to weight ratio, and good fatigue properties and ease of handling. Carbon-FRP (CFRP) bars can provide superior performance and durability, but they are not cost competitive with Glass-FRP (GFRP) bars, which are the most commonly used in civil engineering applications.

In order for FRP bars to become widely accepted in the construction industry, all aspects of their structural behavior must be studied to guarantee their safe application. Bond development is a critical issue for their successful application as reinforcement in concrete structures. Bond characteristics affect the anchorage of bars, strength of lap splices, required concrete cover, and serviceability and ultimate states. The continued integrity of the bond is also a critical issue for the long lasting performance of concrete structures reinforced with FRP bars.

Since several types of FRP bars are commercially available, with varying compositions and surface treatments, the interface bond of FRP bar-concrete is complicated and quite different from that of steel reinforcement. Moreover, it is recognized that FRP bars, especially GFRP bars, are susceptible to attack under exposures to moisture, alkaline solutions and elevated temperature [1–3]. In particular, the durability of GFRP bars can be affected by the alkaline environment of concrete. Since environmental attacks begin at the bar surface, the FRP-concrete bond will be particularly affected by FRP bar degradation. The resin matrix has a major role in transferring forces from the surrounding concrete to the composite FRP bar, while the matrix is also the first constituent material subject to environmental attack.

In addition, it is well known that the coefficients of thermal expansion (CTE) of FRP bars are different in the longitudinal and transverse directions. The longitudinal CTE, depending on fibers, is lower than that of concrete and even negative (as in case of CFRP), while the transverse CTE, depending on matrix, is about 3–10 times larger than that of concrete. Therefore, thermal fluctuations can lead to mismatch of transverse thermal expansions between FRP and concrete, resulting in bond degradation and even concrete cracking. The effects of concrete environment on FRP and mismatch of thermal expansions between FRP bar and concrete are major concerns on bond degradation and concrete cracking.

Considerable research efforts have been conducted on the bond behavior of FRP bars in concrete. Due to differences in FRP products and test methods used, the reported results in the literature showed varied bond strengths and behaviors. Even so, the general bond characteristics of FRP bar can be summarized as follows. The bond strength of FRP bars (with surface deformations) is typ-

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ically within 40–100% of that corresponding to deformed steel bars [4]. Smooth bars develop only 10–20% of bond strength of deformed bars. Surface deformations with a height at least 6% of the bar diameter are necessary to develop adequate bond behavior to concrete. Square bars develop superior bond strength than round bars due to more pronounced wedging effect [5]. Larger diameter bars develop less bond strength possibly due to more shear lag and Poisson effect [5–6]. The average bond strength decreases with the increase of embedment length due to the nonlinear bond stress distribution along the bar [5–6]. The bond strength is lower when the bar has more than 305 mm of concrete cover below, due to the upward migration during casting of air, water and fine particles ("top bar effect") [7]. The addition of transverse reinforcement does not improve the bond strength [7]. Due to its low modulus of elasticity, the slip of FRP bar relative to surrounding concrete is greater than that of steel bars, and, unlike steel bars, the post peak bond strength of FRP bars significantly affects the calculation of development length [6].

Pullout tests, beam tests and splice tests are the most commonly used test procedures to evaluate the bond behavior. As an economical and simple solution for the evaluation of bond performance, pullout test is widely adopted, but it usually results in un-conservative bond strength values. This is because of the compressive stress induced in the surrounding concrete (usually under tension in practical conditions) and the confining action of reaction plate developed in the test specimen. The splitting of concrete during pullout testing is usually avoided by providing relative large volume of concrete surrounding the bar.

It is well established that the bond strength of steel bars is proportional to the square root of concrete compressive strength ($\sqrt{f'_c}$). But this may not be true for FRP bars. The pullout failure mode of FRP bars is usually different from that of deformed steel bars. The bond strengths from several pullout tests of FRP bars vs. $\sqrt{f'_c}$ were collected from the literature as shown in Fig. 1. These data are based on FRP bars with glass or carbon fibers, diameters of 6–19 mm, and embedment lengths of 4–18 bar diameters. For comparison purpose, the bond strengths used in design guides are also plotted in the figure. It can be seen from Fig. 1 that bond strengths adopted in CSA-S806 [15] and JSCE [14] are conservative, while the constant limit given in ACI 440 [16] may not be conservative when concrete strength is low. As shown in Fig. 1, when concrete compressive strength is relatively low, bond strengths are proportional to concrete strength, but for strength approximately above 30 MPa, this correlation is not apparent. The explanation for this behavior may be as follows. Generally, for concrete compressive strength below 20 MPa, the bond strength is primarily governed by interface concrete failure due to induced cracking and tensile stresses as in the case of steel bars. For concrete with higher strength beyond about 30 MPa, the interface mode of failure is due to a combined effect of concrete and surface FRP material degradation, with failure being increasingly dominated mainly by FRP bar surface damage as concrete strength increases. The surface of FRP bars generally includes a resin-rich layer and the interface of this layer with fibers inside. Therefore, the pullout resistance characterized by bond failure mainly occurring within the bar surface can be treated as a possible upper-limit bond capacity of FRP bar-concrete.

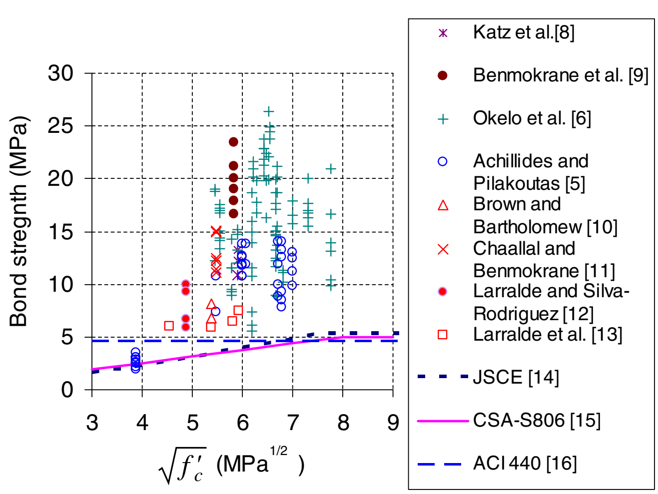

Fig. 1. Bond strengths vs. square root of concrete compressive strength. (See above-mentioned references for further information).

Several studies have been conducted on the durability performance of interface bond between FRP bar and concrete. Bank et al. [4] reported an experimental study on the effects of material degradation of FRP bars on FRP-concrete bond strength and stiffness. Pullout tests were employed to investigate the bond characteristics of FRP bars, and photographs and scanning electron microscopy (SEM) images were used to study the nature of the material degradation in the matrices and fibers. They proposed a descriptive model to relate the reduction in bond strength and stiffness to the degradation of constituent materials in FRP bars, showing good correlations. But their study did not take into account the possible change of concrete compressive strength after exposure, which also affected the bond behavior. Porter and Barnes [17] found that the pullout bond strength of GFRP bar did not decrease when testing bars embedded in concrete and conditioned in solutions at a temperature of 60 °C. Experiments by Bakis et al. [18] showed that after 28-day immersion in 80 °C saturated solution of $Ca(OH)_2$ followed by 5-day drying before embedment in concrete, the ultimate bond strength of GFRP bar did not decrease, while material degradation of GFRP bars was observed. Recently, Galati et al. [19] reported that a 200 h exposure of GFRP-concrete specimens to air at 70 °C resulted in up to 16% bond strength reductions.

From the literature review above, few studies have investigated the effects of FRP bar surface characteristics on bond capacity and post peak bond strength (bond slip curves). Additional studies are needed for evaluating bond strength of FRP bar with high strength concrete, and further research is needed to investigate the bond failure modes of FRP bar- concrete interface and their dependency on concrete compressive strength. There is no standard test method for the durability performance of FRP bar-concrete interface bond. Also, there is limited and inconsistent information on durability performance and degradation mechanism of interface bond under various environmental conditionings.

Thus, in this study, in order to distinctly evaluate the durability performance of the interface bond due to FRP bar degradation, a concrete mix with average compressive strength of 60 MPa was used. The bond behaviors of FRP bars under direct pullout conditions are studied for different material compositions and surface characteristics, and the bond slip curves and failure modes are discussed. The effects of moisture, elevated temperature and thermal cycles on bond behaviors are investigated. Also, the environmental effects on concrete compressive strength, FRP bars, and bond interface are examined.

2. Experimental investigation

2.1. Materials

Four types of FRP bars as shown in Fig. 2 were used in this study. The surface of GFRP1 and GFRP2 bars were helically

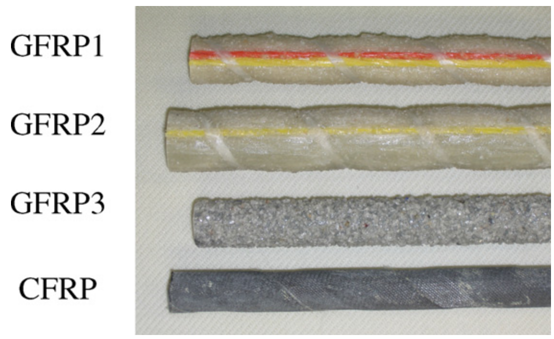

Fig. 2. FRP bars.

wrapped and slightly sand coated. The GFRP3 bar had a sand-coated surface. The surface of the CFRP bars was roughened by sand-blasting to produce deformations. The detailed properties of the four FRP bars are listed in Table 1; all four were commercially available and produced by pultrusion. Concrete was cast in four batches with the following mix design per m^3: 380 kg cement, 730 kg sand, 1140 kg aggregate, and 171 kg water. The 28-day compressive strengths were in the range of 57–63 MPa.

2.2. Specimens and test setup

For pullout test specimens, the FRP bars were cut into 900 mm lengths, and the encasing concrete cylinders had dimension of 150 mm height and 150 mm diameter. The FRP bars were concentrically embedded in the concrete cylinders with bond lengths of five bar diameters. In order to control the bond length, the FRP bar was prepared with a bond breaker, which consisted of soft plastic tubing inserted around the bar to prevent contact of FRP with concrete. These specimens were fabricated by positioning the bars vertically through a wood alignment guiding frame as shown in Fig. 3. The concrete cylinder specimens, with embedded FRP, were removed from the plastic molds one day after casting, and then placed in a curing tank for 27 days before they were subjected to the environmental conditioning as described in the next section.

To evaluate the effects of conditioning on the concrete strength, concrete cylinders with diameter of 100 mm and height of 200 mm were prepared. Moreover, to inspect the interface between FRP-concrete visually, concrete cylinders with embedded FRP bars were cast with diameter of 150 mm and height of 300 mm. These concrete cylinders with embedded FRP bars were split after conditioning, to remove the bars and obtain samples for SEM analyses to evaluate FRP material degradation due to the environmental conditioning. These specimens were cast from the same batches of concrete and were conditioned in the same manner as those corresponding to the pullout specimens. Besides the pullout tests, the purpose of the experimental work was to evaluate the effects of environmental conditioning on factors such as concrete strength,

Table 1
Properties of FRP bars

Bar type	Fiber	Matrix	Diameter (mm)	CTE ($\times 10^{-6}$/ °C)		Tensile strength (MPa)	Young's Modulus (GPa)
				Transverse	Longitudinal		
GFRP1	E-glass	Vinyl ester	9.5	33.7	6.58	856	45.8
GFRP2	E-glass	Vinyl ester	12.7	33.7	6.58	690	40.8
GFRP3	E-glass2	Vinyl ester 2	9.5	35 ~ 37	5.5 ~ 6.4	840	49.4
CFRP	Carbon	Epoxy	9.0	74 ~ 104	−9 ~ 0	2587	124

Fig. 3. Setup for fabrication of pullout specimens.

material degradation of FRP bars, and FRP-concrete interface, all of which can influence the bond behavior of FRP bars.

The schematic arrangement of the pullout test is shown in Fig. 4. Displacement transducers (LVDTs) were used to measure the slip at both the free-end and loaded-end. The effect of axial extension of the FRP bar was subtracted from the data recorded by LVDT2. There was a 10 mm wooden plate placed between the concrete cylinder and supporting steel block to prevent bending or movement due to the irregularities at the contact surface of the cylinder during loading. Split steel pipes were bonded to the

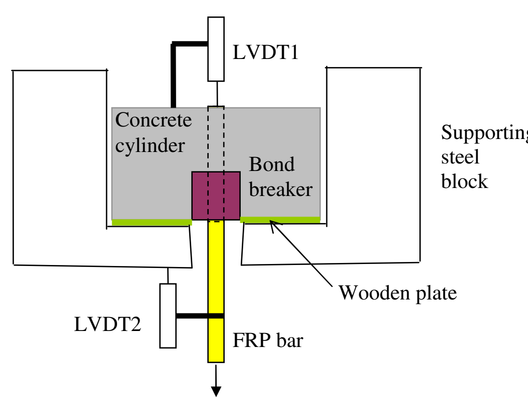

Fig. 4. Pullout test configuration.

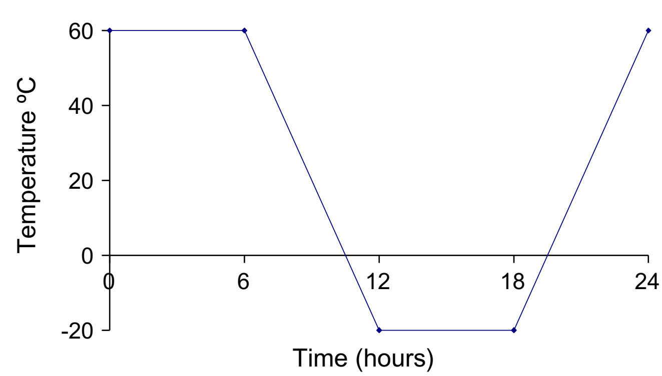

Fig. 5. One-day thermal cycle.

Table 2
Testing plan

Specimen types	Bar type	Control	Environmental exposure		
			W	T	E
Pullout	GFRP1	3	3	3	3
	GFRP2	3	3	3	3
	GFRP3	3	3	3	3
	CFRP	3	3	3	3
Concrete cylinders for compressive strength		3	3	3	3
		3	3	3	3
		3	3	3	3
		3	3	3	3
FRP-concrete cylinders for extraction	GFRP1		1	1	1
	GFRP2		1	1	1
	GFRP3		1	1	1

W: 90 days in water at room temperature; T: 90 days in water at 60 °C; E: 30 days thermal cycling in air.

Fig. 7. Concrete bond failure of pullout test [2].

bar end to protect the bar from crushing within the grip zone during axial loading [2]. The pullout tests were carried out in a Baldwin machine, and the load was applied in a displacement control mode with a maximum rate of about 0.15 kN/s.

2.3. Environmental conditioning and testing plan

The specimens were conditioned in three different types of environments. After 27 day immersion in a curing tank, the first group of specimens was submerged for 90 days in a conditioning tank filled with tap water at room temperature (W). The second group of specimens was immersed for 90 days in tap water maintained at 60 °C in custom-designed double-walled temperature-controlled tanks (T). The final group of specimens was conditioned for 30 days in a programmable environmental chamber (model CSZ ZH-16) for 24-h repeated thermal cycles in air (E) as shown in Fig. 5. One group of unconditioned specimens was first tested to evaluate testing procedures, before other specimens were subjected to

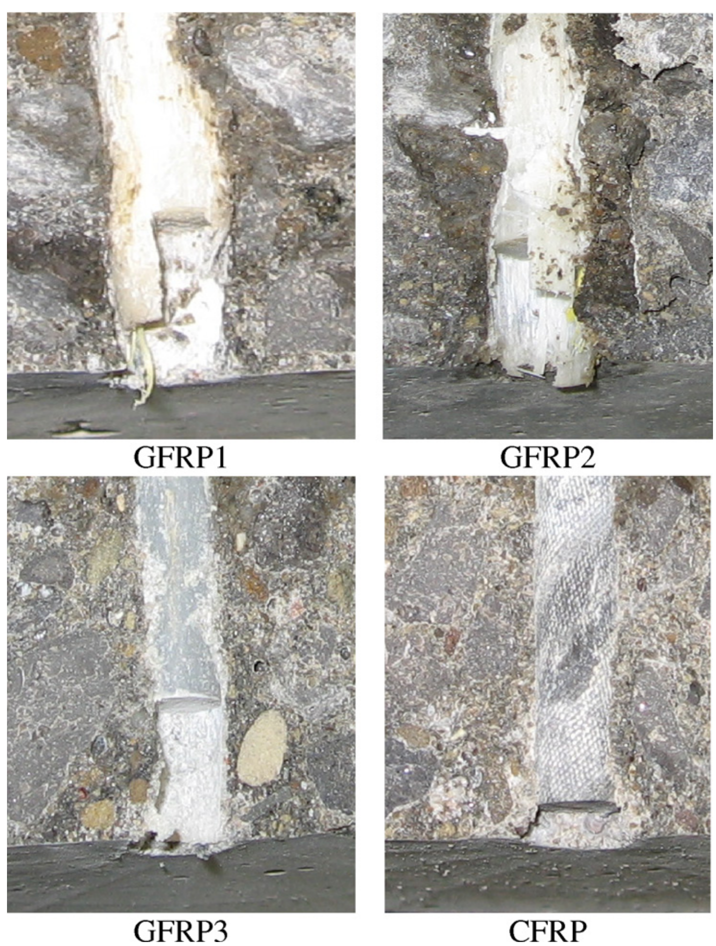

Fig. 6. Typical FRP-surface bond failure modes of pullout tests.

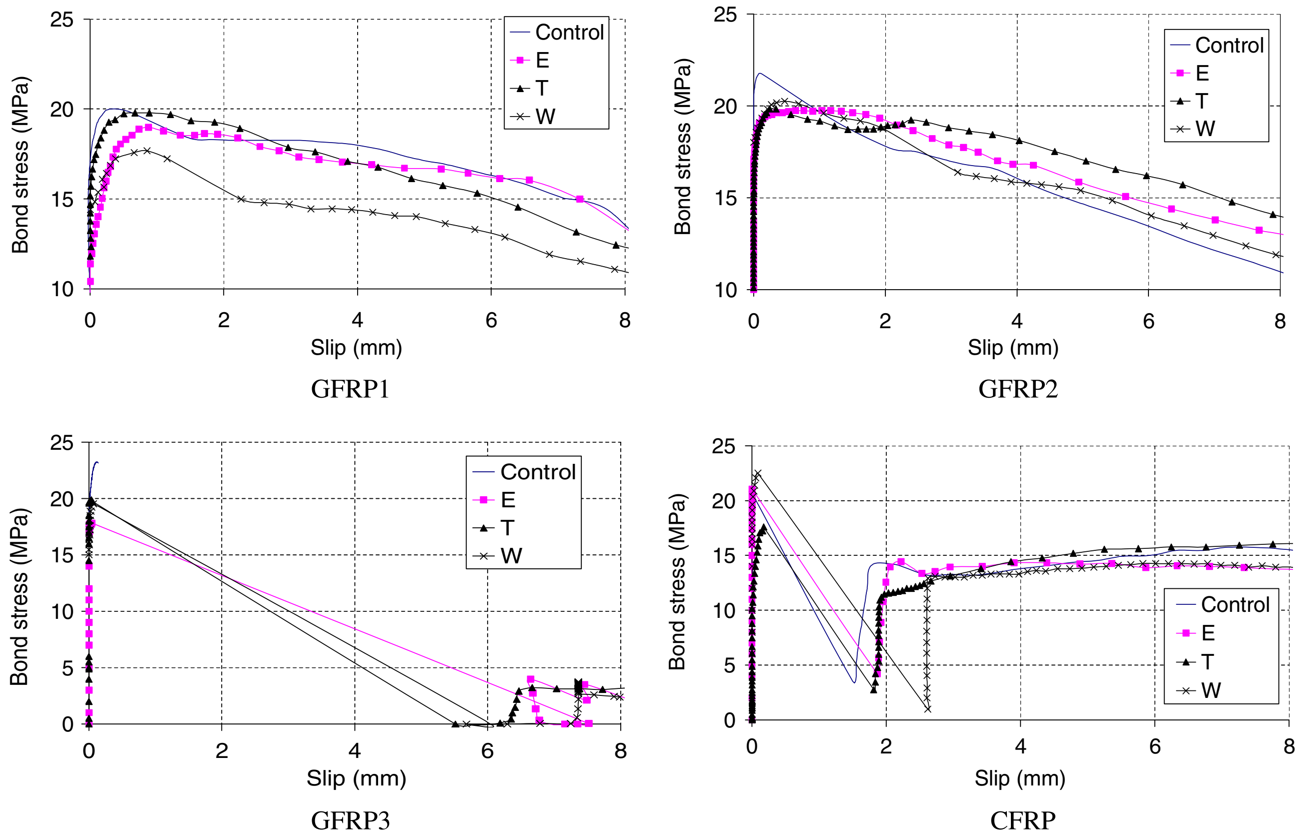

Fig. 8. Comparison of typical free-end slips.

environmental and testing protocols. The testing plan is summarized in Table 2.

3. Experimental results and discussion

3.1. Pullout test

All specimens under pullout tests failed by exhibiting slip through the free-end. After the pullout tests, concrete cylinders were split to check the bond failure mode. As shown in Fig. 6, surface matrix and fiber materials of GFRP bars were still attached to concrete, while the core section of bars had been pulled out. For GFRP3 bars, the sand coating layer was totally stripped from the bar surface. For GFRP1 and GFRP2 bars, bond failure usually happened within the interfaces of resin-rich layer and fibers inside. For GFRP3 bar, the bond failure usually happened within the interfaces of the sand coating layer (sand embedded in resin-rich layer) and core-bar. The bond failure for GFRP bar specimens occurred consistently at the bar surface as expected. For CFRP bar specimens, the bond failure observed was minor and occurred both in concrete and bar surface. The bond failure modes for both control and conditioned specimens were nearly the same. In contrast to the results of this study, tests performed previously by the present authors [2] showed that the pullout failure mainly occurred in concrete while the bar surface appeared to be intact as shown in Fig. 7; in that case, the GFRP bar was similar to GFRP1 bar described in this paper, but the concrete compressive strength was only about 20 MPa, as opposed to an average of 60 MPa used in the present research.

The typical bond stress vs. free-end slip curves are summarized in Fig. 8. It can be observed that the bond slip behaviors of FRP bars with different surface characteristics were quite different.

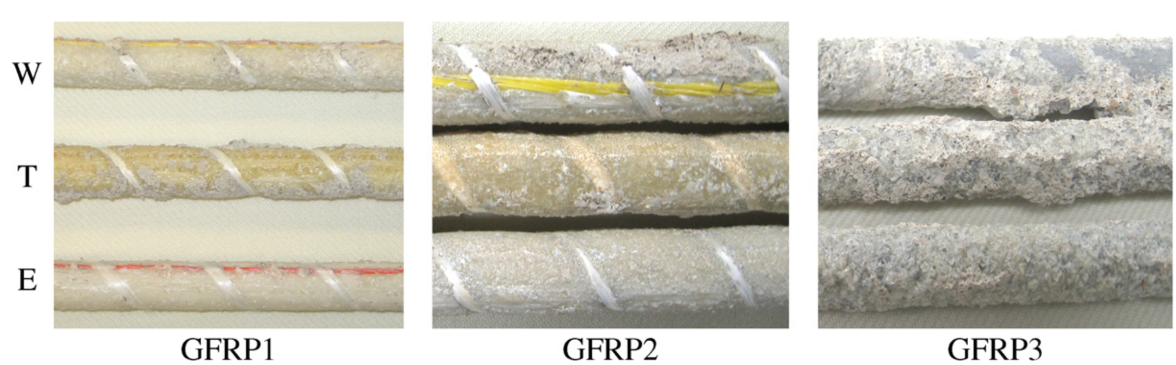

Fig. 9. FRP bars extracted from concrete cylinders after exposure.

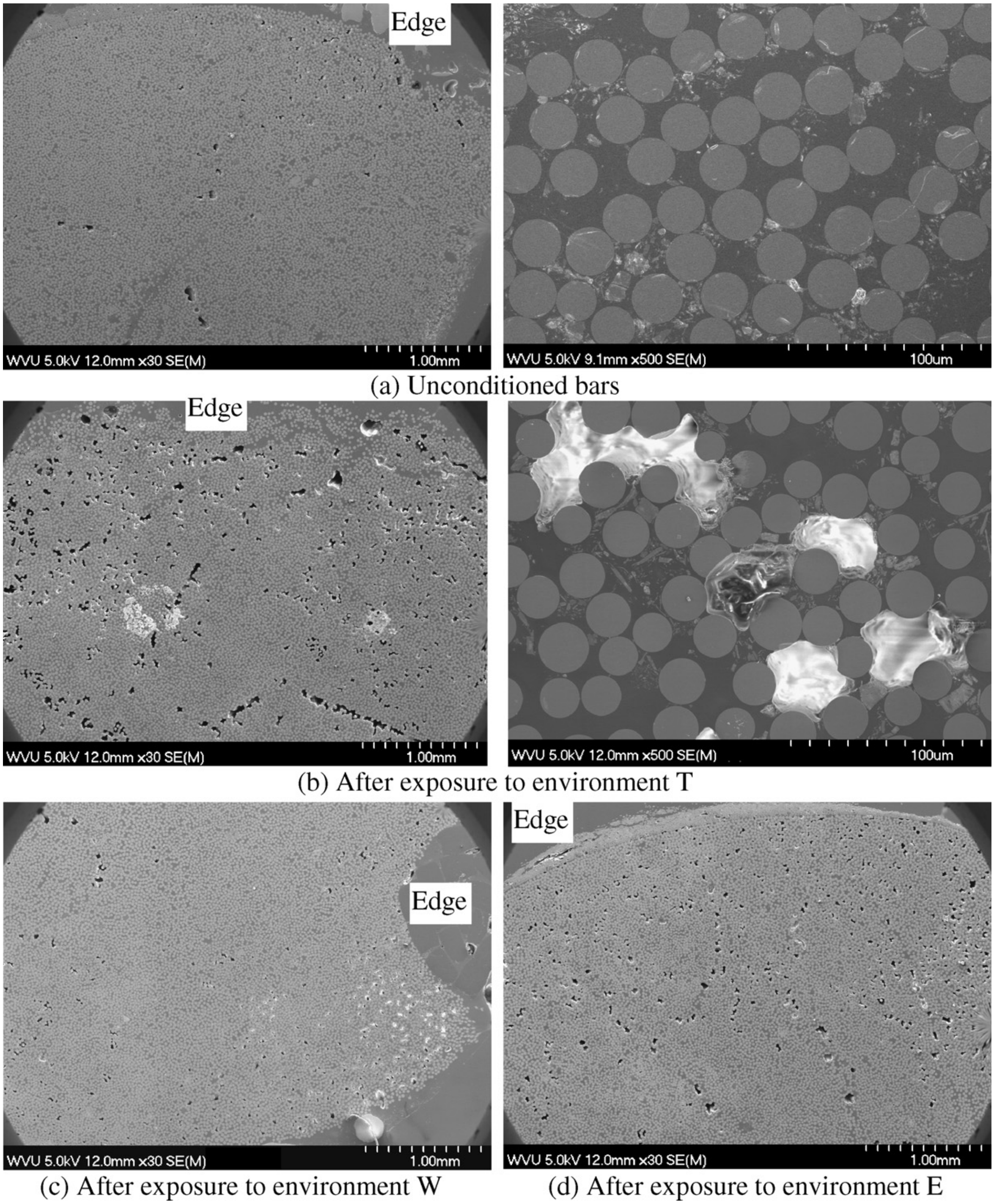

Fig. 10. SEM images of GFRP1 bars.

The bond failures of CFRP bar and GFRP3 bar were relative brittle. The sudden free-end slip was accompanied by significant energy release. During that short moment, there was no data recorded and the pullout resistance seemed to be reduced to almost zero. Subsequently, the friction increased the post peak bond strength to a certain level, followed by continued slip. The post peak bond strength was about 75% of its ultimate bond strength for CFRP bars, while only about 15% for GFRP3 bars. The low post peak bond strength of GFRP3 bars was due to the failure of interface between the sand coating layer and core-bar during the pullout test, as observed in Fig. 6, and the smooth core-bar could not provide much friction. The bond slip curves are similar for GFRP1 and GFRP2 bars since they had about the same pattern of surface deformations.

As shown in Fig. 8, the environmental conditionings exacerbated the free-end slip, especially for those subjected to environment E, affecting the bond strength-slip curves. This behavior was likely caused by the weakened FRP bar surface due to the environmental conditioning. Also, the concrete micro cracking for those in environment E reduced somewhat the restraint against free-end slip. It is noted that for GFRP1 bars, the post peak bond strengths of conditioned specimens were lower than those of control specimens, while the opposite was observed for GFRP2 bars. The reason for this may be in part due to swelling of GFRP2 bar, which had a slightly larger diameter and correspondingly deeper indentations than GFRP1 bar, thus resulting in higher tearing resistance of matrix/fiber constituents from the near surface of the bar during pullout failure.

3.2. FRP bar

In addition to pullout tests, companion concrete cylinders with embedded FRP bars were split after environmental conditioning. The bars were extracted from concrete as shown in Fig. 9. It can be observed that the bar surfaces of specimens exposed to environment E were relatively intact and free of concrete, while attached concrete is shown on the surfaces of those exposed to environments T or W. These results indicated that interfaces (adhesion) for specimens in environment E were weakened due to the micro cracking of concrete, which was likely induced by the mismatch of transverse thermal expansions of FRP bar and concrete. It was also observed through visual inspection that there were much more surface degradations for specimens subjected to environments T or W in case of GFRP1 and GFRP2 bars. Moreover, the color of specimen surfaces was also changed slightly for those conditioned in environment T.

The extracted GFRP1 bars as shown in Fig. 9 were also subjected to SEM analyses. The detailed information for SEM specimen preparation and analysis can be found in Davalos et al. [3]. Typical voids and defects of FRP bar cross sections at high magnification are shown on the right image of Fig. 10b. Since such voids and defects are highly localized, the SEM images for FRP bar cross sections with low magnification (left images of Fig. 10a and b, and both images of Fig. 10c and d) are shown, to provide overall representative results. There are voids shown in unconditioned GFRP1 bar, which are mainly due to the manufacturing process. For conditioned GFRP1 bars, there is a distinct increase in the number and sizes of voids which were induced by environmental conditioning. The SEM images with high magnification give a closer view of matrix, fibers and voids. As shown in Fig. 10b, the closer view of voids on the right image reveals that the matrix was damaged while the degradation of fibers was not obvious. It can be concluded that GFRP1 bars in specimens subjected to environment T had the most degradation (as shown in Fig. 10b), followed by those exposed to environment E (Fig. 10d), and then environment W (Fig. 10c). From a previous durability study on GFRP bars conducted by Davalos et al. [3], the tensile strength retention for GFRP1 after exposure to environment T was much less (62%) than for exposure to environment W (93%), which support the results obtained from SEM analyses as shown in Fig. 10.

3.3. Concrete

Concrete cylinders were also tested for compressive strengths after exposures. The test results are listed in Table 3. There was obvious strength increase for concrete exposed to environment W. The conditioning of environment T resulted in about 20% compressive strength reduction for concrete. The bond strength vs. concrete compressive strength of companion specimens is plotted in Fig. 11. As expected, no apparent dependence of bond strength on concrete compressive strength can be found, as was purposely planned to primarily induce and study FRP-bar damage effect on bond strength with concrete.

3.4. Discussion

Test results in terms of bond strength values are summarized in Table 3. Compared to the test results of other studies as shown in Fig. 1 (Okelo and Yuan [6]; Achillides and Pilakoutas [5]), the bond strength values for untreated specimens in this study were high, but within the range of reported possible values. From Table 3, it can be observed that untreated GFRP3 bar had better bond strength than the other three FRP bars due to its sand coating surface. But about 18% bond strength reduction was recorded for GFRP3 bar specimens after exposures to environment W or E. This reduction was due to the degradation of interface of the sand coating layer over the bar, as indicated by the observed bond failure. For GFRP1 bar specimens, the bond strength degradation was in the range of 8–18% due to environmental conditioning. The bond strength reduction was mainly due to the degradation within the bar surface, as observed visually from companion split samples (Fig. 6). Compared to GFRP1 bars, less degradation of bond strength was found for GFRP2 bars. The reason for this may be that GFRP2 bar had a larger diameter and correspondingly more pronounced surface deformations, which increased the FRP-concrete mechanical interlocking, especially for swelled GFRP2 bars after exposure. Although the bar surface showed nearly the same extent of degradation as GFRP1 bar, much more tearing of matrix/fiber material was shown around the indentations. Negligible bond strength reduction was found for CFRP bar specimens, due to their superior durability performance as found in a previous study [2].

Table 3
Bond strengths of FRP bars

Bar type	Concrete strength (MPa) (Retention %)	Specimen No. 1	2	3	Average bond strength (MPa)	COV (%)	Bond strength retention (%)
Control							
GFRP1	63.4	20.08	20.02	18.74	19.61	3.9	100
GFRP2	62.7	21.79	19.79	22.58	21.38	6.7	100
GFRP3	58.7	22.95	24.07	23.23	23.42	2.5	100
CFRP	57.3	25.35	20.45	20.98	22.26	12.1	100
Environment W							
GFRP1	74.1(117)	17.71	18.71	13.41	16.61	17.0	84.7
GFRP2	68.3(109)	20.26	22.30	21.42	21.33	4.8	99.7
GFRP3	64.7(110)	16.21	19.58	20.70	18.83	12.4	80.4
CFRP	68.0(119)	22.72	20.80	18.53	20.68	10.2	92.9
Environment T							
GFRP1	48.3(76)	19.89	14.40	19.61	17.97	17.2	91.6
GFRP2	51.9(83)	19.84	21.77	20.75	20.79	4.7	97.2
GFRP3	47.7(81)	24.16	19.89	22.39	22.15	9.7	94.6
CFRP	46.1(80)	17.83	19.58	22.72	20.04	12.4	90.1
Environment E							
GFRP1	57.9(91)	14.03	19.02	15.43	16.16	15.9	82.4
GFRP2	59.4(95)	20.96	17.1	19.66	19.24	10.2	90.0
GFRP3	56.7(97)	16.87	17.83	23.20	19.30	17.7	82.4
CFRP	58.7(102)	21.15	21.33	21.33	21.27	0.5	95.6

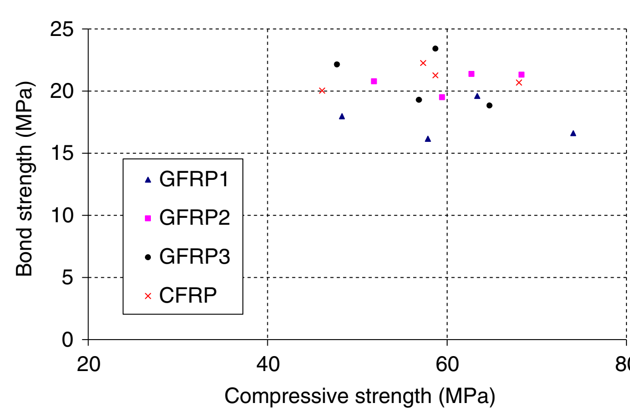

Fig. 11. FRP bar bond strengths vs. Concrete strengths.

Surprisingly, less bond strength reduction was found for specimens exposed to environment T than for those in environment W or E, while at the same time more strength reduction of concrete (Table 3) and material degradation of GFRP bars [2] were found for environment T. The reason for this phenomenon may be that the FRP bars absorbed more water and swelled under environment T, which increased their mechanical interlocking and friction, and thus countered the effect of FRP-bar surface degradation. Moreover, since the bond failure occurred within the FRP-bar surface, the reduction of concrete strength had little effect on bond strength.

Environment E resulted in significant bond strength reduction for GFRP bars. One reason for the reduction may be the micro cracking of concrete introduced by the mismatch of thermal expansions between FRP bar and concrete. The other reason may be the degradation of FRP bars as observed in SEM analyses due to the conditioning of the specimens. However, for CFRP bar specimens, less bond strength reduction was observed even though their transverse thermal expansion coefficient is much higher than for GFRP bars, as listed in Table 1. Therefore, we can conclude that the dominant bond degradation mechanism for GFRP bar specimens in environment E was due to material deterioration of the bar itself. The negligible bond strength reduction for CFRP bar specimens after exposure to environment E would indicate that the micro cracking of concrete was probably not extensive, due mainly to the low transverse Young's modulus of the FRP bar governed by the resin matrix.

4. Conclusions and recommendations

On the basis of the experimental investigation in this study and corroborating results in the literature, the following concluding remarks can be made.

(1) For the concrete with high compressive strength used in this study, the pullout bond failure for GFRP bars mainly occurred within the bar surfaces. In this case, the bond strength of FRP bars was not controlled by the concrete strength. But when concrete has a relatively low strength, bond failure depends on concrete compressive strength and is due mainly to concrete failure.
(2) The bond strength obtained in this study can be considered an upward bound bond capacity of the FRP bars tested, for which the post peak bond strength (bond slip curve) depends significantly on bar surface characteristics. CFRP bars and GFRP3 bars had relatively brittle bond behavior, and GFRP3 bars maintained little post peak bond strength due to the failure of the sand coating layer.
(3) Environmental conditioning resulted in bond strength reduction of about 4–10% for CFRP bars and 0–20% for GFRP bars. The conditioning also increased the free-end slip before the ultimate bond strength was reached; while the bond failure mode was consistently due to bond degradation caused mainly by the deterioration of the FRP bars. As anticipated, CFRP bars had better bond durability performance than GFRP bars.
(4) In case of environment T, material degradation of FRP bars did not necessarily introduce bond strength degradation. The reason for this phenomenon might be that FRP bars may absorb water and swelled under environment T, which increased the mechanical interlocking and friction with concrete, resulting in less bond strength reduction in relation to reductions in environment W or E.
(5) The thermal cycles (environment E) not only introduced micro cracking of concrete, but also degraded GFRP bars. The effect of micro cracking of concrete contributed to free-end slip before ultimate strength was reached, but bar degradation was still the dominant degradation mechanism of interface bond (see discussion of last paragraph in Section 3.4).

Based on the present test results, some recommendations for future study can be made.

The swelling of FRP bars within the confining concrete cylinders need to be considered in future studies, perhaps by drying the specimens to minimize frictional bond strength contributions. Further research is required to define efficient accelerated ageing methods for FRP-concrete interface bond, since for example and contrary to expectations, the conditioning in environment T did not accelerate the bond strength reduction of pullout specimens. Additional effort is needed to develop standard test methods for durability of FRP bar-concrete interface bond, including environmental exposures, duration of conditionings, and more importantly long-term durability predictions. The durability performance of GFRP bars subjected to thermal cycles in moist concrete can be used as a possible testing protocol to be adopted in practice upon further investigation and refinement. In addition to pullout tests, the durability of interface bond strength due to concrete shear failure also needs to be studied.

For GFRP3 and other similar bars, improving the interface bond between sand coating and core-bar can increase the bond performance of these bars in concrete. The bond strengths of FRP bars are related to material properties and surface characteristics of bars (e.g., geometric indentations, coatings), since bond failures observed in this study occurred primarily within bar surfaces. These results can be used to define appropriate local bond slip traction laws needed for numerical modeling of bond behaviors due to material degradation of FRP bars.

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