Cement & Concrete Composites 32 (2010) 461–467

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Effect of aging on bond of GFRP bars embedded in concrete

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ARTICLE INFO

Article history:
Received 3 June 2009
Received in revised form 25 February 2010
Accepted 27 February 2010
Available online 6 March 2010

Keywords:
Durability
FRP
Glass
Aging
Interface
Bond strength
Mechanical properties
Microstructure

ABSTRACT

This paper presents an experimental investigation of the durability of the bond between GFRP bars and concrete, specifically as it relates to degradation of the GFRP-bar surface and behavior of the bar–concrete interface. The GFRP bars were embedded in concrete and exposed to tap water at 23 °C, 40 °C, and 50 °C to accelerate potential degradation. The bond strengths before and after exposure were considered as a measure of the durability of the bond between the GFRP bars and concrete. In addition, Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), and scanning electron microscopy (SEM) were used to characterize how bar aging affected the bond between the GFRP bars and the concrete. The results showed that aging did not significantly affect the durability of the bar–concrete interface under the conditions used in this study.

1. Introduction

Infrastructure decay due to corrosion of embedded reinforcing steel stands out as a significant challenge worldwide. The main long-term deterioration mechanism involves moisture diffusion and the transport of dissolved harmful chemicals within the concrete, which can affect internal reinforcement. Glass-fiber-reinforced polymer (GFRP) materials have not been used in large-scale construction applications despite their numerous advantages over traditional materials such as steel. Yet the long-term performance of GFRP remains unresolved under some special conditions, such as in highly alkaline environments. Indeed, the strength of the glass fibers, polymer matrix, and the fiber–matrix and bar–concrete interfaces can decrease in moist alkaline environments. Nevertheless, GFRP's low cost-to-performance advantage is driving its worldwide use and acceptance. GFRP materials are considered to provide high strength, while being lightweight, noncorrosive, and nonconductive.

Wide acceptance of FRP components in the construction industry requires comprehensive investigation of their structural and mechanical behavior to ensure their suitability for civil-engineering applications. Bond development is a critical issue for their successful application as internal reinforcement in concrete structures [11]. Bar anchoring, lap-splice strength, required concrete cover, and serviceability and ultimate states are all affected by bar bond characteristics. The bond's long-term durability also plays a critical role in the long-term performance of concrete structures using internal FRP reinforcement [11].

Several investigations have been carried out to determine GFRP durability under environmental conditions that could occur under actual service conditions [15,12,9]. Moreover, FRP bars—especially GFRP bars—are susceptible to attack under exposure to moisture, alkaline solutions, and elevated temperature [9,10]. In addition, it is well-known that the coefficients of thermal expansion (CTE) of GFRP bars are not the same in the longitudinal and transverse directions [16]. The longitudinal CTE—depending on fibers—is lower than that of concrete, while the transverse CTE—depending on matrix—is about 2–4 times greater than that of concrete. Therefore, thermal gradients can lead to mismatching of transverse thermal-expansion values between FRP and concrete, degrading the interface between FRP bars and concrete and even resulting in concrete cracking. The effects of concrete environment on FRP and the mismatch of CTE between FRP bars and concrete are major concerns affecting the long-term bond behavior of concrete structures with internal GFRP reinforcement.

Considerable research has gone into the bond behavior of FRP bars in concrete [17,13,1,7] and the durability performance of the bond between FRP bars and concrete. For example, Porter and Barnes [14] found that the pullout bond strength of GFRP bars did not decrease when testing bars embedded in concrete and aged in solutions at a temperature of 60 °C. On the other hand, Bakis et al. [6] showed that, after 28 days of immersion in a saturated $Ca(OH)_2$ solution at 80 °C followed by 5 days of drying, the

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doi:10.1016/j.cemconcomp.2010.02.010

ultimate bond strength of GFRP bars embedded in concrete did not decrease, although material degradation of GFRP bars was observed. Recently, Davalos et al. [11] found that conditioning different types of GFRP bars embedded in concrete in water at room temperature and 60 °C reduced the bond by about 20%. Clearly, FRP components and test methods significantly influence conclusions drawn about the durability of the FRP bar–concrete interface. Davalos et al. [11] have also shown that the failure mode of bond is dependent on the profile of the surface of the bar and coating layer that is usually added to enhance the bond performance.

Designers and owners have concerns about the performance and long-term adhesion properties at the interface between concrete and GFRP bars. This study sought responses to such issues through simulating field conditions: immersion of concrete-wrapped GFRP bars in tap water and characterizing the long-term performance of the concrete–bar interface. In particular, the main objective of this study is to characterize the long-term durability of the interface between GFRP bars and concrete with pullout tests. This economical test is commonly used to assess bond behavior, even if it does not allow for direct measurement of design strength. The conditioning used in this study is more consistent with field conditions because the FRP material is embedded in concrete.

2. Experimental program

2.1. Material

Sand-coated GFRP bars manufactured by a Canadian company (Pultrall Inc., 2005) were used in this study (Fig. 1). The GFRP reinforcement was made of continuous longitudinal E-glass-fiber strands bound together with a thermosetting vinylester resin using a pultrusion process. A coating of sand particles of a specific grain-size distribution further enhances the bonding potential. The glass's mass fraction was 78.3%, determined by thermogravimetric analysis according to ASTM E 1131 [4]. The relative density, according to ASTM D 792 [3], was 2.04 and the nominal diameter 19 mm. Bar mechanical and physical properties—measured during preliminary tests—are summarized in Table 1. All bars were cut into 1200-mm lengths as specified by ACI 440.3R-04 B3 [2]. The concrete mixture consisted of 380 kg of Type 10 cement (corresponding to ASTM I cement), 730 kg of fine aggregate, 1140 kg of coarse aggregate, and 171 kg of water per cubic meter of concrete. The 28 days compressive strengths ranged from 55 to 62 MPa. A high-strength concrete was used to ensure that failure during pullout occurred at the bar–concrete interface, instead of in the concrete, to characterize environmental impact on the interface's long-term performance. These specimens were 200-mm concrete cubes with a single GFRP bar embedded vertically along the specimen's central axis. The bar's bonded length was five times bar diameter (95 mm). Fig. 2 depicted a typical specimen.

Fig. 1. Surface configuration of a GFRP bar.

Table 1
Mechanical and physical properties of 12.7-mm-diameter GFRP bars.

Property	Units	Value
Mechanical properties		
Nominal tensile strength	MPa	728
Guaranteed design tensile strength	MPa	656
Nominal tensile modulus	GPa	47.6
Tensile strain at failure	%	1.53
Poisson's ratio	–	0.27
Physical properties		
Longitudinal coefficient of thermal expansion	$\times 10^{-6}$/°C	6.1
Transverse coefficient of thermal expansion	$\times 10^{-6}$/°C	23.5
Moisture absorption	%	0.48
Glass content	% volume	65.4
	% weight	74.5

2.2. Test plan

This study involved accelerated aging of GFRP reinforcing bars embedded in concrete. The specimen block were cast and kept at saturated humidity for 40 days before initial conditioning, consisting of complete immersion in tap water at 23 °C for 180 days. The purpose of immersion was to stabilize the concrete's mechanical properties. After completion of initial conditioning, specimen bond properties were measured and served as a baseline for bond properties. The other samples for pullout testing were kept immersed in tap water for additional aging at different temperatures. Previous work at the University of Sherbrooke [18] has shown that long-term degradation was not significantly affected by the type of water used for accelerated aging (tap or deionized). The immersion receptacles were wood containers specially manufactured for the study. A polyethylene sheet was placed on top of the wood containers to avoid excessive water evaporation during conditioning. The bars were separated from each other and the container bottom to allow the tap water to circulate freely between and around the GFRP bars. The water level was kept constant throughout the study

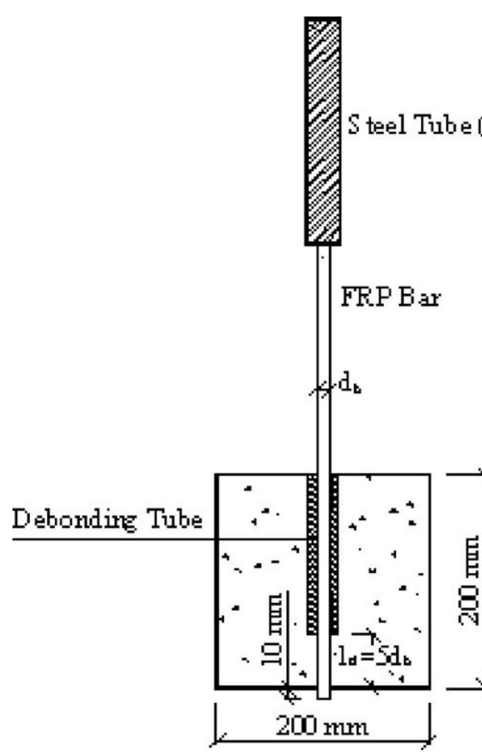

Fig. 2. Dimensions of the pullout specimen.

to prevent the pH from increasing as a result of water evaporation (increased alkaline–ion content). The water temperatures were chosen to accelerate the aging effect, yet not high enough to trigger thermal degradation. The aging conditions in this study aimed at simulating actual application conditions. They were harsher than actual field conditions, however, since the specimens were continuously saturated with water.

Following initial conditioning, specimens were fully immersed at three different temperatures (23 °C, 40 °C, and 50 °C) for three different lengths of time (60, 120, and 180 days). The high temperatures accelerated degradation, as shown by the increased moisture diffusion rates in the concrete and bars. The increased temperature during accelerated aging simulates the effect of time. Accelerated aging also provides information about the long-term behavior of the GRFP-bar–concrete interface. At the end of each period, five specimens were removed from the water and subjected to direct pullout testing to compare their average bond stress, slippage values, and mode of failure to those of the control specimens.

2.3. Pullout tests

All specimens were subjected to direct pullout testing according to ACI 440.3R-04 method B3. Each specimen was instrumented with three linear variable differential transformers (LVDTs) to record elongation during testing. The test was carried out using a Baldwin testing machine; the load applied to the reinforcement bar was 20 kN/min. For each pullout test, the specimen was mounted on the press with steel-pipe anchors gripped by the wedges of the machine's upper jaw. A 200-mm-square steel loading plate 20-mm in thickness with a 25-mm hole drilled through its center was used to load the specimens. Fig. 3 shows the test set-up used for pullout testing. The applied load and bar slippage were recorded during the test with a data-acquisition system. Due to the brittle nature of GFRP, no yielding was found to occur.

2.4. Scanning electron microscopy (SEM)

SEM observation and image analysis were performed to analyze specimen microstructure before and after aging. SEM was used to observe the unconditioned specimens and specimens aged in tap water at 50 °C for 6 months, which produces harsher aging. All specimens for SEM observation were first cut, polished, and coated with a thin layer of gold–palladium using a vapor-deposit process. A JEOL JSM-840A SEM was used for microstructure examination to detect degradation of the polymer matrix, glass fibers, or interfaces.

2.5. Differential scanning calorimetry (DSC)

Twelve to fifteen milligram specimens from both unconditioned and aged samples were sealed in aluminum pans and analyzed in a TA Instruments Q10 differential scanning calorimeter (DSC). Samples were prepared according to the manufacturer's specifications. The specimens were heated from 25 °C to 200 °C at a rate of 10 °C/min. The glass-transition temperature was determined for both specimens in accordance with ASTM E 1356 [5]. Two scans were performed for each specimen and only one specimen was tested for both samples. The first scan is useful in determining the difference of T_g between the control and conditioned specimens. If a decrease of T_g was observed for conditioned samples, this is an indication of plasticizing effect or chemical degradation. The second scan gives information about the degradation mechanism. An upward shift in T_g was observed during the second scan, resulting from post-cure during the first scan. If the T_g of the aged sample measured during the second scan was close to that of the control sample, it may be assumed that a reversible plasticizing effect induced by moisture absorption occurred. On the other hand, if the T_g was lower, it may be concluded that a irreversible chemical degradation occurred.

2.6. Fourier transform infrared spectroscopy (FTIR)

One specimen was taken directly from both unconditioned and aged samples, and analyzed with Nicolet Magna 550 spectrometer equipped with an attenuated total reflectance (ATR) device. Fifty scans were routinely acquired with an optical retardation of 0.25 cm to yield a resolution of 4 cm^{-1}.

3. Tests results and discussion

3.1. Bond-strength retention

The bond-strength results are summarized in Table 2. Fig. 4 shows the evolution of the bond strength of bars according to immersion duration at various temperatures. The values of the

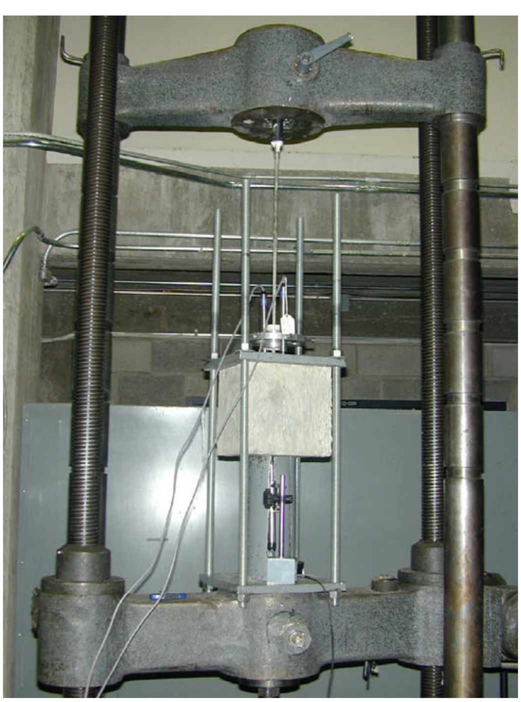

Fig. 3. Pullout-test setup and instrumentation.

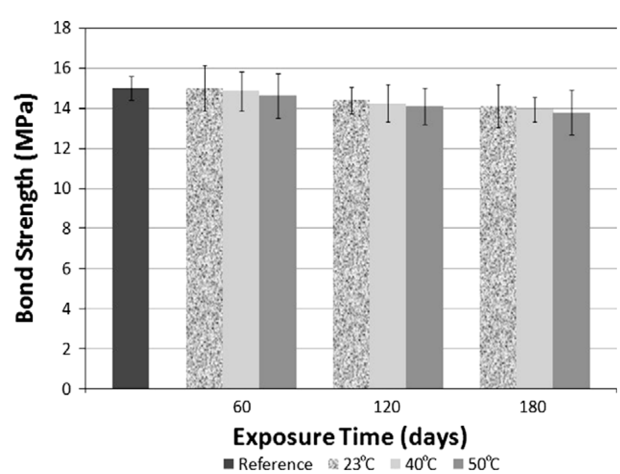

Fig. 4. Bond-strength evolution of conditioned GFRP bars at 23 °C, 40 °C, and 50 °C.

Table 2
Bond strength of GFRP control samples and environmentally exposed samples.

	Temperature of immersion (°C)	Average bond strength (MPa)	COV (%)	Bond strength retention (%)
Reference(after initial conditioning)		15.0	4.0	100
60 days immersion in water	23	15.0	7.6	100
	40	14.9	4.5	99
	50	14.6	7.3	98
120 days immersion in water	23	14.4	6.7	96
	40	14.3	6.4	95
	50	14.1	4.4	94
180 days immersion in water	23	14.1	7.9	94
	40	14.0	6.2	93
	50	13.8	8.9	92

measured bond-strength retentions are 100%, 99%, and 98% for immersion temperatures of 23 °C, 40 °C, and 50 °C, respectively, after 60 days of immersion. The values of the measured bond-strength retentions are 94%, 93%, and 92% for immersion temperatures of 23 °C, 40 °C, and 50 °C, respectively, after 180 days of immersion. The bond strength was only slightly affected by water immersion, whereas immersion temperature had no major effect on bond-strength retention. Bond-strength reduction was very low after 6 months of complete immersion (less than 8%), even at very high temperature (50 °C).

3.2. Mode of failure

All specimens tested under pullout tests failed by exhibiting slip through the free-end. After the pullout tests, the concrete blocks were split to check the bond failure mode. As shown in Fig. 5, the GFRP-bar surface matrix and fiber materials were still attached to the concrete, although the bar core sections had been pulled out. The bond failure usually occurred at the interface of the concrete and sand coating and/or at the interface of the sand coating and bar. Failure occurred there because of the concrete's high shear strength, which exceeded the strength of these interfaces. Fig. 6 illustrates this mode of failure, focusing on the bonded length (embedment length) of the GFRP bars after failure. The control and conditioned specimens exhibited the same bond failure modes.

3.3. Bond stress-slip relationship

The free-end slip was recorded directly using the LVDTs (see the typical bond stress vs. free-end slip curve in Fig. 7). The free-end slip and curve shape were similar for the control and conditioned samples. The bond failures of the GFRP bars were relatively brittle. The sudden free-end slip was accompanied by a significant energy release. During that short time, no data were recorded and the pullout resistance seemed to drop to almost zero. The low post-peak bond strength of the GFRP bars resulted from failure at the interface between the sand coating and core-bar during the pullout test, as depicted in Fig. 6. The smooth-core bar could not provide enough friction to resist to the applied pullout load.

Fig. 6. Details of the embedded length after failure.

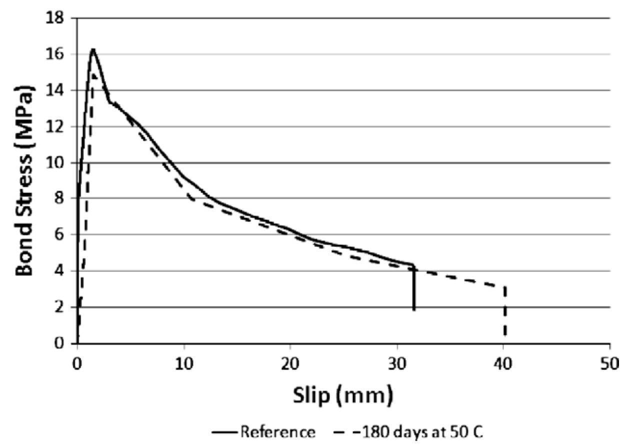

Fig. 7. Bond stress–slip relationship for 19-mm GFRP bars.

3.4. Microstructural effects

3.4.1. GFRP bar/sand-coating interface

Visual and microstructural examination revealed no significant interface damage after initial conditioning of 180 days in tap water at 23 °C, followed by 180 days of immersion in tap water at the highest temperature (50 °C). The micrographs in Fig. 8 show the interface between the fiber–resin mixture and the silica coating

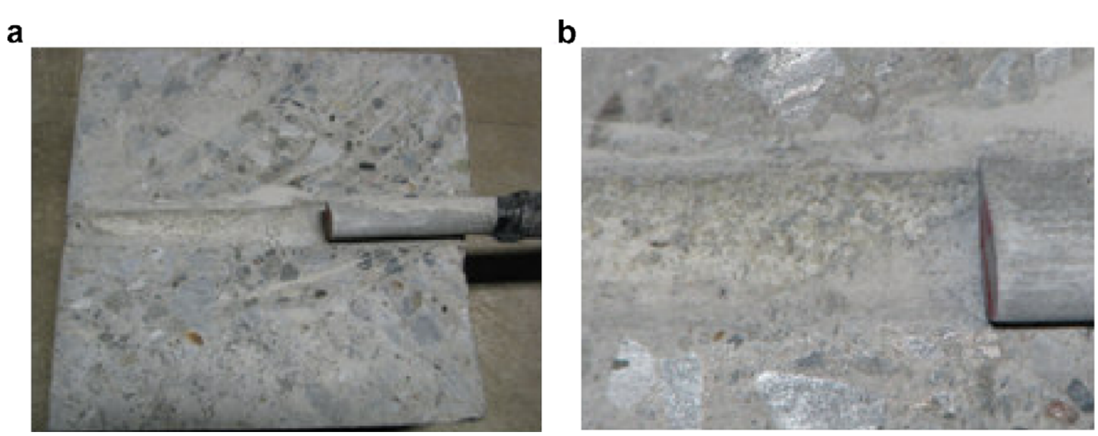

Fig. 5. Concrete bond failure of pullout test.

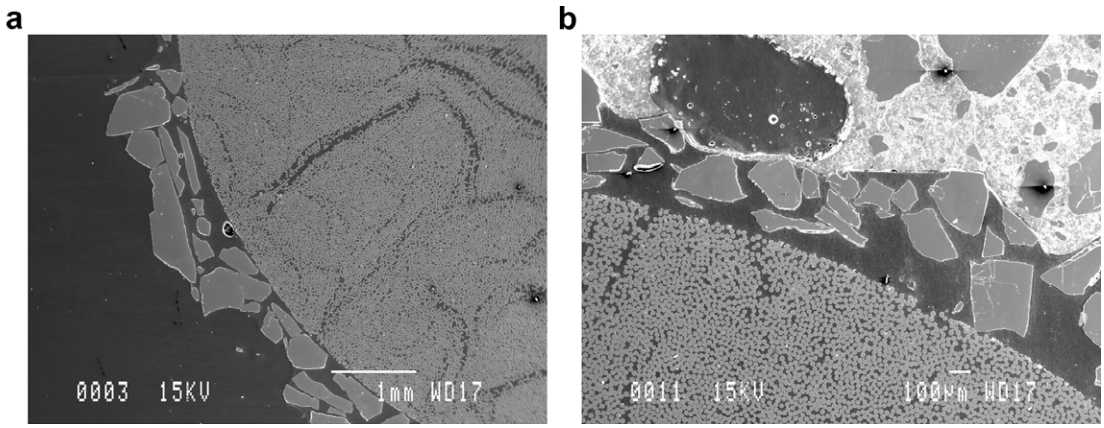

Fig. 8. Micrograph (X20) of the bar–sand-coating interface.

on an unconditioned GFRP bar and a concrete-wrapped GRFP bar aged in tap water for 360 days (180 days at 23 °C and 180 days at 50 °C).

Analysis of these interfaces and microstructure generally revealed that the conditioning did not affect the microstructural properties of the GFRP bars. This contradicts what several researchers had observed when similar GFRP bars were directly immersed in an alkaline solution [8,9]. This phenomenon clearly illustrates that the GFRP bars and the bar–coating interface was not significantly affected by accelerated aging.

3.4.2. Interface between the GFRP bar and concrete

The three main components of the bond between GFRP reinforcing bars and concrete are: (1) chemical adhesion, (2) mechanical interlocks, and (3) friction. If any resin or fiber degradation occurs at the interface, these components and the durability of GFRP reinforced structure could be affected. Fig. 9 shows the concrete–bar interface (low and high magnification) for concrete-wrapped GFRP bars conditioned in water at 23 °C for 180 days and at 50 °C for another 180 days. No significant interface damage is apparent. The loss of bond strength could also be explained by a reduction in shear strength at the concrete–sand coating interface due to moisture saturation of the concrete and moisture absorption in the sand coating.

3.5. Effects on GFRP bars

FTIR analysis was performed on unconditioned and on embedded 19-mm bars conditioned in water at 23 °C for 180 days and at 50 °C for another 180 days (Fig. 10). The most interesting region

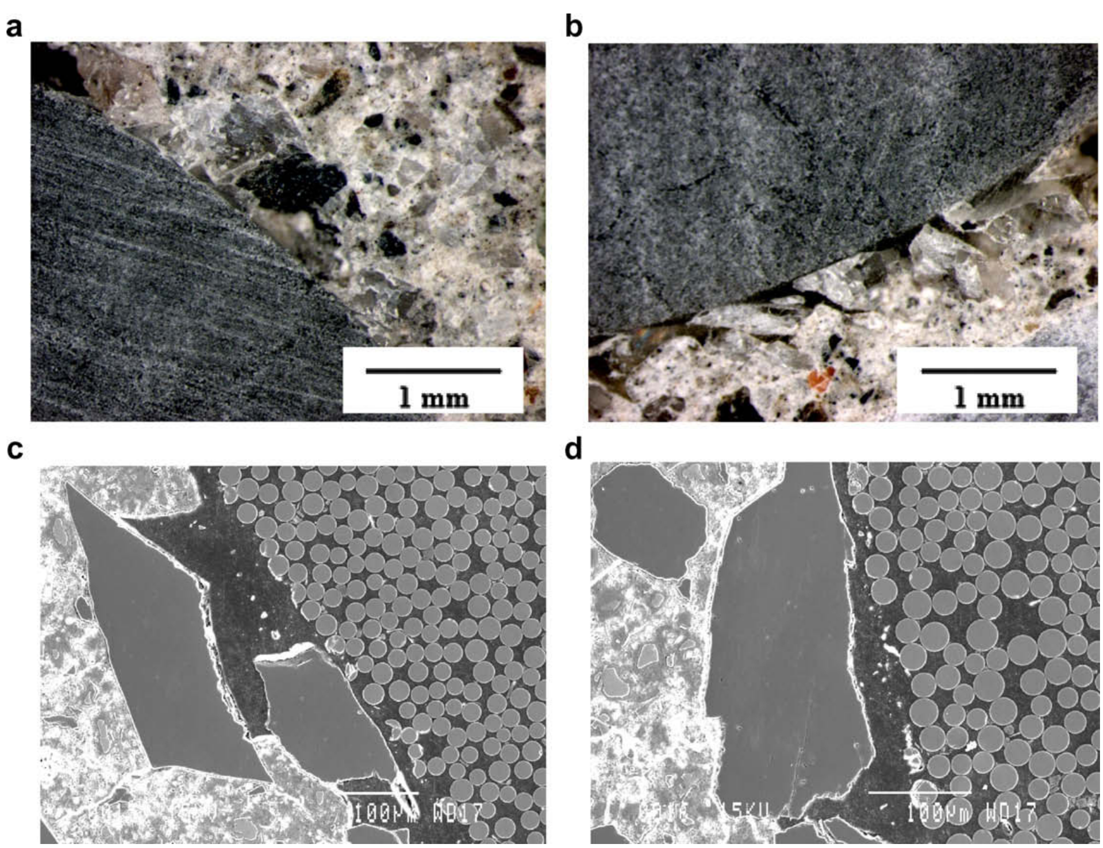

Fig. 9. Micrographs of the GRFP-bar–concrete interface.

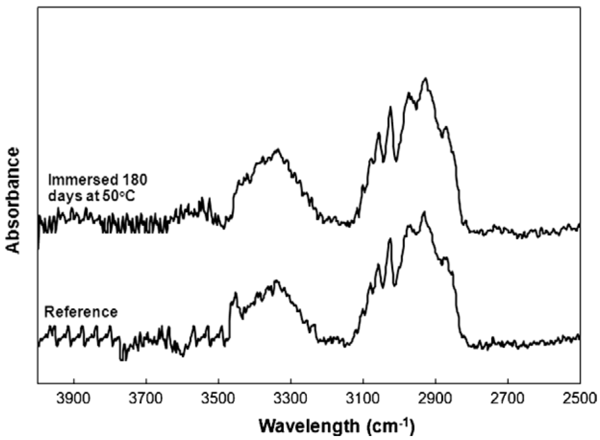

Fig. 10. FTIR spectra of unconditioned and aged samples.

Table 3
Results of differential scanning calorimetry (DSC) analysis.

Conditioning	Temperature (°C)	Duration (days)	T_g run 1 (°C)	T_g run 2 (°C)
Unconditioned			110	129
Embedded in concrete and immersed in water	50	240	103	128

of the FTIR spectra lies between 3300 cm^{-1} and 3600 cm^{-1}, which corresponds to the stretching mode of the hydroxyl groups in the vinylester resin. When a hydrolysis reaction occurs, new hydroxyl groups are formed and the corresponding infrared band increases. Changes in the peak intensity were quantified by determining the ratio of the resin's OH peak to CH stretching peak, which was not affected by the conditioning. The experimental ratio of the resin's OH peak to CH stretching peak for the 19-mm diameter embedded samples immersed in water for 180 days at 23 °C followed by an immersion of 180 days at 50 °C was 0.51, compared to 0.45 for unconditioned samples. Therefore, the hydroxyl peak does not show any significant changes. This indicates that no significant hydrolysis occurred in the environmental conditions under study.

Table 3 presents the glass-transition temperatures (T_g) for the first and second heating scans of the unconditioned and aged samples. Note that, in both the unconditioned and aged samples, the T_g values corresponding to the second heating run are higher than that of the first. This shift indicates that the samples had not been fully cured and that a post-curing phenomenon occurred during the first heating run. The results in Table 3 also show no significant changes in T_g values for the specimens aged in water for 360 days (180 days at 23 °C and 180 days at 50 °C). This indicates that DSC analysis detected no major impact effect on the resin's thermal properties as the result of the conditioning.

Based on these observations, we conclude that no major degradation occurred at the polymer level and that the loss of bond properties could not be related to degradation of the GFRP material.

4. Summary and conclusions

Based on these results, the following conclusions may be drawn:

1. The bond strength of GFRP bars decreases as the duration of immersion increases. Even at high temperature (50 °C), when the environment is more aggressive, the change in bond strength remained still minor. For example, increasing the tap-water temperature from 40 °C to 50 °C for 180 days decreased bond-strength by 7%–8% of the original bond strength. The retention values measured are 94%, 93%, and 92% for 180 days of immersion at 23 °C, 40 °C, and 50 °C, respectively, after initial conditioning for 180 days at 23 °C.
2. The bond's failure mode is dependent on the bar's surface profile and the coating layer, which is usually added to enhance bond performance. The tested GFRP specimens failed in pullout due to the sand coating peeling off.
3. No significant microstructural changes in GFRP bars embedded in concrete were observed after 360 days of immersion in tap water (180 days at 23 °C and 180 days at 50 °C). The bar–concrete and the resin–fiber interfaces were not apparently affected by moisture absorption and high temperature.
4. The polymer matrix was not affected by moisture absorption and high temperature: differential scanning calorimetry revealed no changes in the glass-transition temperature. FTIR did not show any significant changes in the polymer's chemical structure (e.g., degradation).

Lastly, even if the bond strength was only slightly affected by conditioning in tap water at high temperature, microstructural observations revealed that the interfaces between the concrete and the sand coating and between the sand coating and the bar were not affected. Improving the interface bond between the sand coating and core bar can increase the bond performance of sand-coated bars embedded in concrete. The bond strength of FRP bars are related to bar material properties and surface characteristics (e.g., geometry, coatings), since the bond failures observed in this study occurred primarily at bar surfaces and the effects of accelerated aging on the GFRP bars were negligible. Since these conclusions apply only to the product tested subjected to aging in moist concrete, additional research is needed to study the effect of environmental parameters on bond properties (e.g., bar-surface configuration and concrete mix design).

Acknowledgments

This research was supported by the National Science and Engineering Research Council (NSERC) of Canada, The Fonds québécois de la recherche sur la nature et les technologies (FQRNT), the Ministère des Transports du Québec (MTQ), and the Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada). The authors thank Pultrall Inc. (Thetford Mines, Quebec) for the donation of the GFRP bars.

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