Physical, Mechanical, and Durability Characterization of Preloaded GFRP Reinforcing Bars

Mathieu Robert[1] and Brahim Benmokrane[2]

Abstract: This paper presents the physical, mechanical, and durability characterization of glass fiber-reinforced polymer (FRP) (GFRP) bars subjected to different tensile stress levels. FRP bars were first loaded at levels up to 20, 40, 60, and 80% of their ultimate tensile strength (UTS) which could create cracks and microcracks in the FRP bars and affect the long-term durability of the product. Microstructural observations were conducted on preloaded GFRP reinforcing bars to show the deterioration of fiber, matrix, and the fiber/matrix interface. Moisture absorption and tensile properties of loaded bars were also measured to estimate the potential effects of cracks and microcracks on durability-related properties and on short-term mechanical properties, respectively. Loaded bars were also embedded in a moist mortar at elevated temperature to perform accelerated aging. The measured tensile strengths of the loaded bars before and after exposure were considered as a measure of the durability performance of the specimens. Results showed that the GFRP bars start to be slightly affected by the tensile stress at 60% of the UTS. These results showed that the loading of GFRP bars did not have a dramatic effect on the durability of the bars even when a pronounced tensile stress, which was approximately 80% of the UTS, takes place.

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Introduction

Glass fiber-reinforced polymer (FRP) (GFRP) materials have emerged as a practical alternative material for producing reinforcing bars for concrete structures (Chen et al. 2006, 2007; Robert et al. 2009). This is due to their relatively low cost-to-performance ratio and noncorrosive nature compared to traditional steel reinforcing bars. In addition, GFRP materials exhibit properties, such as high tensile strength, which make them suitable for use as structural reinforcement. However, their durability in an alkaline environment is still of concern and factors that can affect the long-term behavior of GFRP materials have to be investigated. Considerable research has been conducted in the past decade to assess the suitability of FRP reinforcement in reinforced concrete structures (Riebel and Keller 2007; Karbhari et al. 2007; Chen et al. 2006). The work of these researchers had highlighted on the short-term performance of FRP reinforced concrete structures or on the durability of FRP reinforcing bars subjected to aging in alkaline solution. Some researchers have reported on the durability of FRP bars embedded in moist concrete which simulate the real conditions of application and also on the adverse effects of the presence of cracks and microcracks in the FRP bars on their long-term durability (Robert et al. 2009).

It was recognized that FRP bars, especially GFRP bars, were susceptible to attack under exposures to moisture, alkaline solutions, and elevated temperature (Chen et al. 2006, 2007). In particular, the durability of GFRP bars could be affected by the alkaline environment of concrete and moisture absorption. The moisture diffusion into FRP composites could be influenced by anisotropic and heterogeneous character of the material. Along with diffusion into the matrix, wicking through the fiber/matrix interface in the fiber direction could be a predominant mechanism of moisture ingress (Apicella et al. 1982; Prian and Barkatt 1999). Nonvisible dissociation between fibers and matrix could lead to rapid losses of interfacial shear strength (Ashbee and Wyatt 1969). In aggressive environments, diffusion into polymers could become non-Fickian due to chemical reactions that decompose the material and change the diffusion rate. Therefore, researchers have attempted to control diffusion by using resin matrix with lower permeability, modifying the interphase region with suitable sizing agents or selecting appropriate molding processes to reduce void content (Benmokrane et al. 1998; Benmokrane and Robert 2006). However, the initial diffusion stages normally could be approximated as Fickian (Apicella et al. 1982; Liao et al. 1999). As environmental attacks begin at the bar surface, the presence of cracks and microcracks in the bar itself could significantly affect the long-term durability of GFRP reinforcing bars (Benmokrane et al. 2006).

FRP composites show several degradation mechanisms when exposed to moisture, which, depending on the pH value of the solution (acidic or alkaline), develop more or less intensively. Alkaline solutions, which were supposed to simulate the pH of concrete environment, provoked etching bond breaking processes that could attack silica-oxygen network and lead to glass dissolu-

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tion (Paul and Youssefi 1978; Scholze 1982). The matrix could be damaged through cracking and microcracking due to volume expansion during moisture absorption, whereas its stiffness could be reduced by plasticization. A subsequent mechanism of degradation by breaking of polymer chains triggered by hydrolysis and leaching out of low molecular weight material from the bulk resin further could damage the matrix (Ashbee et al. 1967; Ashbee and Wyatt 1969; Abeysinghe et al. 1982). Glass fibers were damaged due to the combination of two processes: (1) chemical attack on the glass fibers by the alkaline cement environment and (2) concentration and growth of hydration products between individual filaments (Murphy et al. 1999). In addition, it was stated that calcium, sodium, and potassium hydroxides present in concrete pore solution could attack glass fibers (Benmokrane et al. 2002). Thus, it is clear that the durability of GFRP materials is related to the solution absorption, which is strongly affected by the presence of cracks and microcracks in the bar.

Therefore, the objective of this paper focuses on the investigation of the influences of cracks and microcracks in GFRP bars on their short- and long-term behaviors. The study is carried out using multiple performance data obtained from mechanical and physical characterization. Tensile, physical, and microstructural properties are investigated after preloading to evaluate the effects of cracking on short-term performance of preloaded GFRP bars. The long-term durability of preloaded bars is also investigated by accelerated aging of mortar-wrapped preloaded bars in tap water at high temperature.

Experimental Program

Material

Sand coated glass FRP bars manufactured by a Canadian company are used in this study. The bars are made of continuous E-glass fibers impregnated in a vinylester resin using the pultrusion process. The glass transition temperature of the polymer matrix is 112°C and is determined by differential scanning calorimetry (DSC) according to ASTM E1356 ASTM 2008standard. The mass fraction of glass is 81.5% and is determined by thermogravimetric analysis according to ASTM E1131 (ASTM 2003) standard. Their specific density according to ASTM D792 (ASTM 2000)standard is 1.99. GFRP bars have a nominal diameter of 12.7 mm and their average ultimate tensile strength (UTS) and modulus of elasticity, measured in accordance with ASTM D7205 (ASTM 2006) standard, were 854 MPa and 43 GPa, respectively. Bars are preloaded by tensile test prior to mechanical and physical characterization and microcracking due to transient loading that might take place in real service conditions is considered via the preloading regime. All bars prepared for tensile preloading are cut of length equal to 1,440 mm as specified by the ASTM D7205 standard. The bars are divided into three series: (1) the unconditioned reference samples; (2) the unconditioned preloaded samples without mortar cover; and (3) the conditioned samples preloaded prior to being embedded into mortar (60 bars).

The experimental program is defined by the organization chart presented in Fig. 1. The mortar mixture used for bar casting consisted of three parts of sand, one part of Type I cement according to ASTM C150 (ASTM 2005a) standard and a water/cement ratio of 0.40 which led to a mortar pH of 12.15 measured by the extraction of the interstitial solution after aging. The mortar was poured only in the middle third of the bars to avoid any degradation at the ends which were used as grips during the tensile tests.

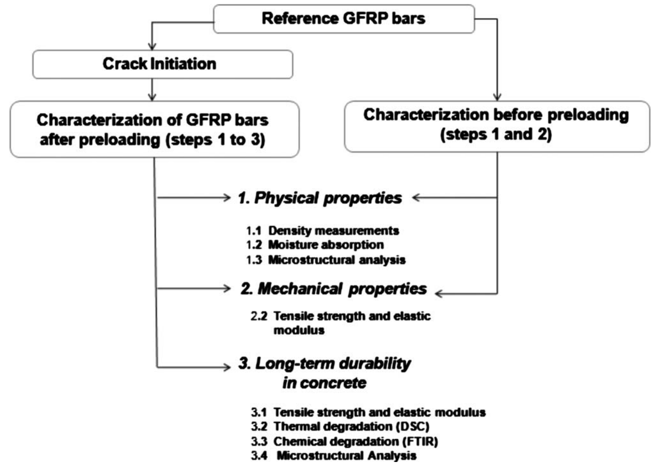

Fig. 1. Organization chart of the experimental program

The mortar mold of the envelope was made of wood having a square section of 48 mm that gave a minimum mortar cover of 18 mm [ACI 440.5-08 (ACI 2008)].

Preloading of GFRP Bar Samples

Before aging, GFRP bars were preloaded at four different tensile stress levels—20, 40, 60, and 80% of their theoretical UTS (854 MPa)—to initiate cracks and microcracks in polymer and glass fibers. All bars were preloaded under tension according to ASTM D7205 standard. The test was carried out using a MTS 810 testing machine and load was increased until required load was reached. For each tensile preloading, the specimen was mounted on the press with the steel pipe anchors gripped by wedges of the upper and the lower jaws of the machine. The rate of loading ranged between 250 and 500 MPa/min and the maximum load was maintained for 10 min and then was reduced at the rate of 250–500 MPa/min.

Moisture Absorption

After preloading of GFRP bars, the moisture uptake measurements at saturation were made by immersing a few preloaded specimens without mortar cover in tap water for one month at temperature of 50°C. Some specimens were removed from water, wiping them dry and measured their weights, according to ASTM D570 (ASTM 2005b) standard. The percentage moisture uptake was calculated and the gain in mass was corrected to take into account possible mass loss of the specimens due to various dissolution phenomena, such as hydrolysis, by drying later completely the immersed specimens by placing them in an oven at 100°C for 24 h and comparing their masses to their initial masses.

Density Measurements

The density of the reference and preloaded composite samples without mortar cover was determined by displacement in water according to ASTM D792 (Test Method A) using a Mettler AG204 DeltaRange microbalance. The specimens (three per sample) were weighed in air (P_S). Then, each specimen was placed in a cylinder, which was filled with water. After having weighted the cylinder containing the sample and water (P_{S+W}), the specimen was removed and the cylinder was filled with water up to the same level. The cylinder containing only water was then weighed (P_W). If considering the density of water as equal to 1.00, the density of the sample, ρ, was obtained using Eq. (1)

$$\rho = Ps/Ps + Pw + Ps + w \quad (1)$$

A drop of density was considered as a confirmation of the increase in void content and as a measurement of the damage caused to the GFRP bars by preloading.

Tensile Strength Retention after Preloading

After conditioning, all bars were tested under tension according to ASTM D7205 standard and using the same parameter used in preloading procedure. The results for reference samples and samples preloaded at 80% of the UTS, which corresponded to the harsher conditioning, were compared in order to measure the effect of potentially high stress level on short-term mechanical properties of GFRP bars. Long-term durability of preloaded samples was also estimated by testing embedded samples aged in water at different times of immersion. Each specimen was instrumented with a linear variable differential transformer to capture the elongation during testing. The test was carried out using MTS 810 testing machine and the load was increased until failure. The applied load and bar elongations were recorded using a data acquisition system monitored by a computer.

Long-Term Durability

Sixty bars were embedded in mortar after preloading at 80% of the UTS and subjected to different agings. Accelerated aging of these GFRP reinforcing bars was achieved by using a method in the study to simulate an aggressive alkaline environment of the saturated mortar. The embedded samples immersed in tap water were different as compared to the conventional accelerated aging test bars which were directly immersed in alkaline solutions. The technique currently used in the present research was more representative of the real life situation. Indeed, the pH of the solution surrounding the bars was a result of the absorption of water by the mortar, thus allowing the liberation of the alkaline ions of the mortar directly in the environment of bars. The aging was performed by immersing mortar-wrapped GFRP bars in a wooden container specially fabricated for the study. A polyethylene sheet was also placed on top of the wood containers to avoid evaporation of water during the conditioning. Bars were separated from each other and from the bottom of the container to allow free circulation of the solution between and around GFRP bars. Furthermore, the water level was kept constant throughout the study to avoid pH increase which could be due to concentration of the alkaline ions in the solution. The temperatures of immersion were chosen to accelerate the degradation effect of aging; however, they were not too high to produce any thermal degradation mechanisms.

The specimens were completely immersed at three different temperatures (23, 40, and 50°C). The specimens were removed from the water after 60, 120, 180, and 240 days. These conditionings were chosen to simulate the long-term durability of GFRP bars according to the Arrhenius law. These conditioning parameters are similar to those used in previous studies on durability of GFRP bars embedded in concrete (Robert et al. 2009). Six GFRP bars were removed from the water and tested for tension to compare their tensile strength retention values to those observed in the reference specimens. There was no change noticed at the surface of GFRP bars due to their immersion in the water at different temperatures.

Fig. 2. View of cement mortar-wrapped GFRP bar specimen

DSC

DSC was used to obtain information on the thermal behavior and characteristics of polymeric materials and composites such as glass transition temperature (T_g), melting point, curing process, crystallinity, thermal stability, and relaxation. In the study, specimens weighting 12–15 mg were cut from different GFRP samples (nonconditioned and specimens aged in moist mortar at 50°C during 240 days after preloading 80% of the UTS) and placed in aluminum pans and were analyzed using a TA Instruments DSC Q10 calorimeter. Specimens were heated from 25 to 195°C at a rate of 5°C/min. Glass transition temperature was determined for both the specimens in accordance with ASTM E1356 standard. If decrease in T_g was observed for conditioned samples, it was an indication of plasticizing effect or chemical degradation. Aged sample maintaining a lower T_g than for the reference showed an irreversible chemical degradation.

Microstructural Observations

Scanning electron microscopy (SEM) observations and image analysis were also performed to observe the microstructure of specimens before and after preloading. Samples observed in the SEM were unconditioned specimens, prestressed at load levels of 20, 40, 60, and 80% of the UTS without subsequent aging and embedded specimens preloaded at 80% of the UTS as well as aged in tap water at 50°C during 240 days. All specimens observed in the SEM were first cut, polished, and coated with a thin layer of gold-palladium by a vapor-deposit process. After coating of surfaces, microstructural observations on transversal and longitudinal surfaces were performed on a JEOL JSM-840A SEM. These observations were conducted to see the potential degradation of glass fibers or interfaces if any.

FTIR

Fourier transform infrared spectroscopy (FTIR) spectra were recorded using a Nicolet Magna-550 spectrometer equipped with an attenuated total reflectance device (Fig. 2). Fifty scans were routinely acquired with an optical retardation of 0.25 cm to yield a resolution of 4 cm^{-1}.

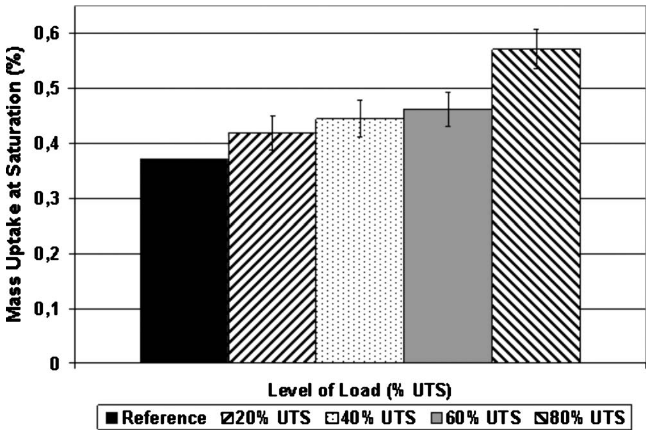

Fig. 3. Mass uptake of reference and preloaded GFRP bar specimen

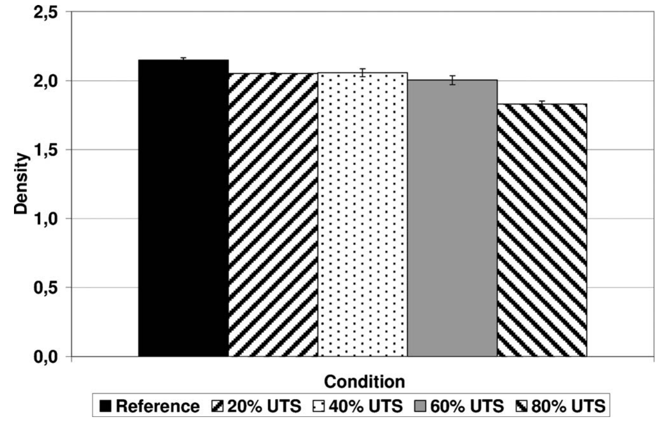

Fig. 4. Measured density of reference and preloaded GFRP bar specimen

Experimental Results and Discussion

Moisture Uptake

Fig. 3 shows mass uptake by different specimens due to tap water absorption. It was seen that the higher the load level, the greater the mass uptake was. In fact, measured saturation levels were approximately 0.35, 0.42, 0.45, 0.48, and 0.57% for specimens preloaded at 0, 20, 40, 60, and 80% of the UTS. Increased moisture uptake could be due to the damage caused to microstructure of samples by the preloading. It could be expected that the higher the load level, the greater the presence of cracks and microcracks induced by the stress. Moisture penetration into composite materials could be of three different mechanisms: (1) diffusion of water molecules inside microgaps between polymer chains; (2) capillary transport into gaps and flaws at the interfaces between fibers and polymer; and (3) transport by microcracks in the matrix formed during compounding process (Abeysinghe et al. 1982). So, it was clear that the preloading at high load level had a great influence on the moisture absorption of GFRP bars affecting the presence of stress induced cracks and the quality of the fiber/resin interface. However, even after preloading of 80% of the UTS the moisture absorption of tested GFRP bars was considerably lower than the specified limit of 0.75% for product certification of FRPs as internal reinforcement in concrete structures according to ISIS Canada specifications (ISIS 2006). Furthermore, it was seen that the moisture uptake increase was more quickly for load levels of 60 and 80% of the UTS as compared to those between 0 and 60% of the UTS. So, it was concluded that the major part of the microstructural damage occurred at very high load level around 80% of the UTS. The highest mass loss in the specimen due to dissolution phenomenon was low at 0.8%. There was also no observed relation between the mass loss and the load level. This low level of mass loss indicated that there was no significant degradation phenomenon affecting the matrix or the fibers during immersion.

Change in Density

Fig. 4 shows the measured density for reference sample and samples preloaded at 20, 40, 60, and 80% of the UTS. As expected, the higher the load level, the lower the density. This result could be explained due to the creation of cracks and microcracks by preloading of GFRP bars. Matrix cracking and debonding at fiber/matrix interface cause an increase in void content of the GFRP bar and decrease in the measured density. This result was in accordance with moisture uptake measurements in the way that decrease in the density was more important between load levels of 60 and 80% of the UTS as compared to that between 0 and 60% of the UTS. Therefore, it was concluded that major part of the microstructural damage, causing the density decrease, occurred at very high load level around 80% of the UTS.

Tensile Properties after Preloading

The tensile test of reference and preloaded specimens showed almost a linear behavior up to failure. Specimens failed by the rupture of fibers. The failure was accompanied the delamination of fibers and resin, as shown in Fig. 5. Micelli and Nanni (2004) also observed similar tensile failure modes of GFRP bars.

Table 1 shows the UTS and Young's modulus for reference bars and for the bar subjected to preloading at 80% of their UTS. Indeed, it was seen from the measured results that after the preloading, no significant loses of tensile strength and elastic modulus occurred and the preloaded bars were not affected by high stress level (80% of the UTS) used for their preloading. These results showed that tensile properties of GFRP bars just after the

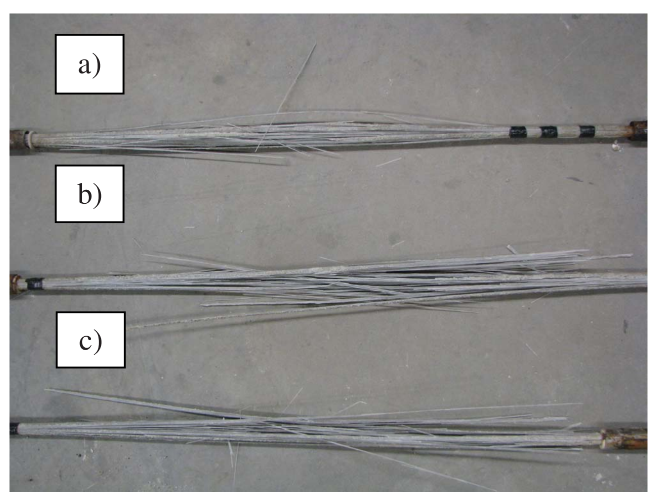

Fig. 5. Typical failure mode of GFRP bars: (a) reference unconditioned specimen; (b) specimen preloaded at 80% of the UTS; and (c) specimen preloaded at 80% of the UTS and aged 240 days in moist mortar at 50°C

Table 1. Tensile Properties after Preloading

Condition	Specimen number	Tensile strength (MPa)	Average UTS (MPa)	COV (%)	Young's modulus (GPa)	Average Young's modulus (GPa)	COV (%)
Reference	1	872	854	2.2	43	43	2.1
	2	866			44		
	3	841			42		
	4	844			43		
	5	847			43		
80% UTS	1	880	851	2.4	43	43	3.1
	2	830			43		
	3	852			42		
	4	835			41		
	5	860			44		

application of high stress level, leading to the creation of cracks and microcracks, were not affected by their preloading at 80% of their UTS.

Long-Term Tensile Property Retention

Table 2 shows the experimental results obtained during the tensile tests concerning the ultimate strength and the modulus of elasticity of reference and preloaded (80% UTS) bars tested after 60, 120, 180, and 240 days of immersion in water at different temperatures. Results presented in Table 2 show slight decrease (6–11%) of the UTS after 240 days of immersion of preloaded bars embedded in mortar. This decrease was similar to the loss of tensile strength measured by Robert et al. (2009) on same bar subjected to same conditionings but without preloading. It can also be seen in Fig. 5, similar mode of failure of reference, preloaded, and aged bars. From this observation, it was concluded that the preloading of GFRP bars and the presence of microcracks in the bar microstructure did not have any significant effect on the long-term properties of the tested sample. Furthermore, it was clear that the temperature of immersion affects the loss of tensile strength GFRP bars. It was seen that for duration of immersion of 240 days, the losses of resistance are equal to 6, 8, and 11% at 23, 40, and 50°C, respectively. This phenomenon was due to the increasing of diffusion rate of the solution into the sample and to the acceleration of chemical reactions of degradation with the temperature of immersion, leading to a larger absorption rate of the solution for the same time of immersion. The absorption of solution could lead to a degradation of the fibers and fiber/matrix interface, leading to a loss of the ultimate tensile.

Concerning the stiffness of embedded preloaded GFRP bars after aging in the water, it was seen from the measured results presented in Table 2 that after 240 days, the loss of elastic modulus was negligible and all aged bars were not affected by the higher temperature or the exposure to moist mortar. This result showed that elastic modulus of bars was not affected by aging in concrete environment and was in accordance with the results found by Robert et al. (2009) on similar bars subjected to same aging but without preloading.

Effects on Polymer Matrix

A FTIR analysis of unconditioned bar specimen and preloaded (80% of the UTS) mortar-wrapped bars and aged in water at 50°C for 240 days was conducted (Fig. 6). The most interesting region of the FTIR spectra is located between 3,300 and 3,600 cm^{-1}, which corresponds to the stretching mode of the hydroxyl groups of the vinylester resin. When hydrolysis reaction occurs, new hydroxyl groups are formed and the corresponding infrared band increases. Changes in the peak intensity are quantified by determining the ratio of the OH peak to the carbon-hydrogen stretching peak of the resin, which is not affected by the conditioning. The experimental ratio of the OH peak to the carbon-hydrogen stretching peak of the resin for the 12.7-mm diameter preloaded mortar-wrapped samples and immersed in water for 240 days at 50°C was 0.53 compared to 0.51 for un-

Table 2. Tensile Properties after Conditionings

Time of immersion (days)	Number of samples	Temperature (°C)	Average tensile strength (MPa)	COV (%)	Average tensile modulus (GPa)	COV (%)
0	5	23	854	2.2	43	2.1
60	5	23	846	5.2	44	3.3
	5	40	847	6.3	43	2.9
	5	50	838	4.2	43	4.1
120	5	23	849	2.4	42	5.2
	5	40	832	8.1	43	4.4
	5	50	837	2.9	44	2.3
180	5	23	836	2.8	42	3.9
	5	40	823	5.1	43	6.2
	5	50	808	3.4	41	4.2
240	5	23	810	3.8	43	3.3
	5	40	784	6.7	42	1.9
	5	50	768	9.1	43	1.8

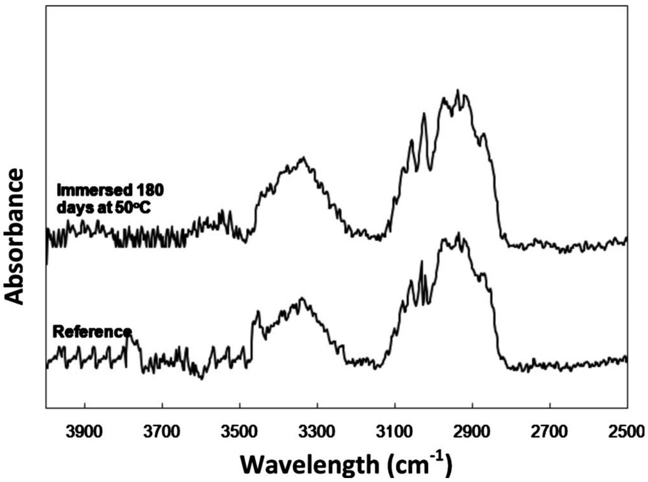

Fig. 6. FTIR spectra for unconditioned and aged samples

conditioned samples. So, the hydroxyl peak did not show any significant changes. This observation led to the conclusion that no chemical degradation of the polymer occurred during the immersion of preloaded mortar-wrapped bars.

Figs. 7 and 8 show DSC scans for the first and second heatings of unconditioned and mortar-wrapped 12.7-mm bars and aged in water at 50°C for 240 days after preloading at 80% of the UTS, respectively. Table 3 presents the glass transition temperature (T_g) values for the first and second heating unconditioned and preloaded aged samples. The thermogram of aged samples shown in Fig. 7 shows two C_p (thermal capacity) changed corresponding to what seems to be two different T_g for this sample. The first T_g at 95°C seemed to show some polymer modification and the second around 113°C corresponded to the reference result. It was concluded by this observation that only a part of the polymer matrix was affected by the aging of GFRP bars. This result could be explained by the fact that the polymer matrix was more exposed to water in region surrounding cracks and microcracks which could cause significant modification in the polymer matrix structure. This shift of T_g to lower temperature was explained by nonreversible chemical reaction, such as hydrolysis, or by reversible physical interaction between the water and the polymer matrix. Since the T_g found in the second run was the same for the reference and the aged sample, it was concluded that a reversible

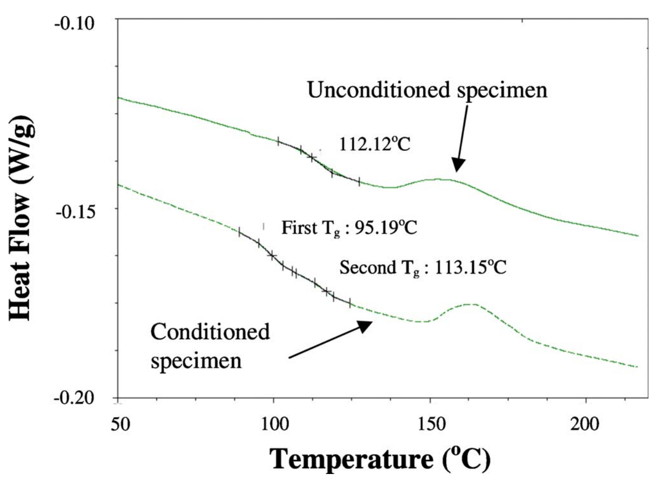

Fig. 7. Thermogram of the first heating run by DSC

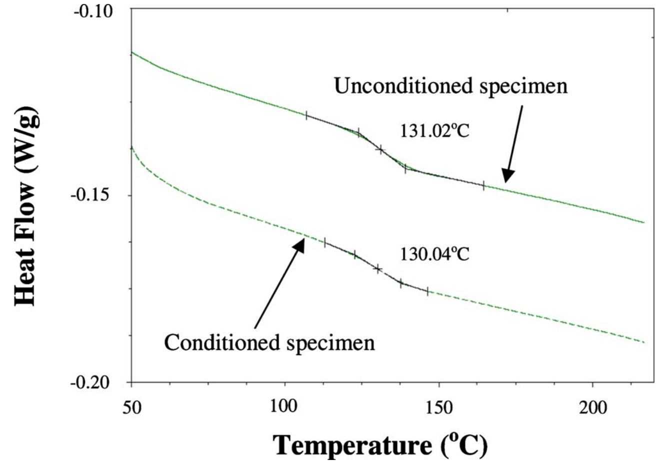

Fig. 8. Thermogram of the second heating run by DSC

degradation (e.g., plasticization of the matrix) occurred and this result was confirmed by the FTIR analysis. It should be noted that for the unconditioned and preloaded aged samples, the T_g corresponding to the second heating run was higher than that of the first scan. This shift indicated that the samples were not fully cured and that a postcuring phenomenon occurred during the second heating run.

Microstructural Observations

Effect of Preloading

The micrographs of Fig. 9 show the longitudinal bar surface of reference and preloaded GFRP bar. In particular, the fibers and the interface between the fibers and the resin should be observed. Observations of these interfaces and of the microstructure in general demonstrated that the preloading affected the microstructure of GFRP bar. In fact, the higher the stress level, the higher the cracking and microcracking. It could also be seen that no significant damage occurred to the resin and to the interface between the fibers and the polymer matrix, even under stress of 80% of the UTS. The only visible damage occurred at the fiber level since the elongation at the rupture was lower for the fibers compared to the polymer matrix. It was also seen that no microstructural change was observed for preloading level less than 60% of the UTS. For these low stress levels, the elongations of fibers and matrix were possible. For stress level higher than 60%, the fibers began to break. These observations were in accordance with moisture uptake and density measurements in the way that the increase in microcracking at high stress levels leads to an increase in moisture uptake and a decrease in density.

Effect of Long-Term Immersion of Preloaded GFRP Bars

Fig. 10 shows micrographs of the fiber/matrix interface for reference [Fig. 10(a)], GFRP bars preloaded at 80% of the UTS [Fig. 10(b)], mortar-wrapped specimen aged in water after a preloading

Table 3. Results of DSC Analysis

Conditioning	Temperature (°C)	Duration (days)	T_g Run 1 (°C)	T_g Run 2 (°C)
Unconditioned	23	240	112	131
Preloaded and aged specimen	50	240	95–113	130

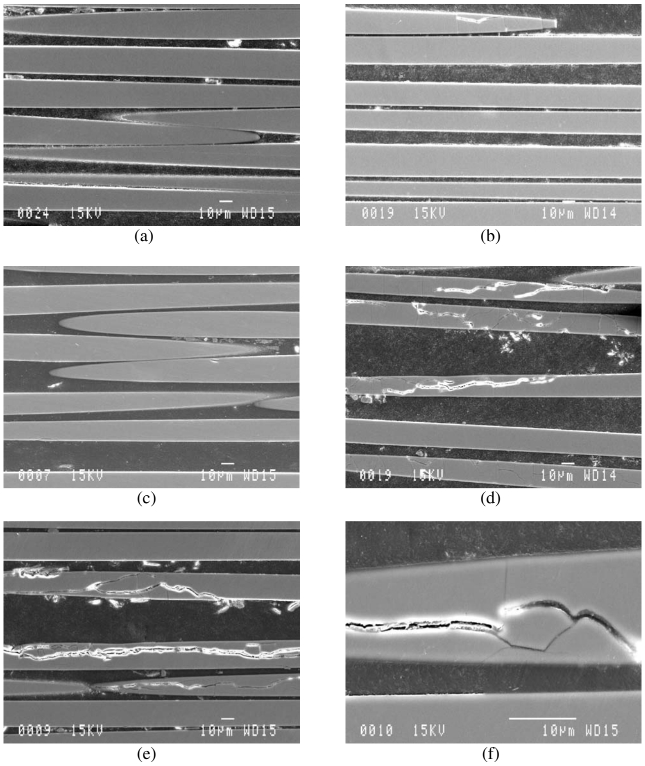

Fig. 9. Micrograph of longitudinal GFRP bar surface preloaded under tensile load: (a) reference GFRP bar at low magnification; (b) GFRP bar loaded at 20% of the UTS at low magnification; (c) GFRP bar loaded at 40% of the UTS at low magnification; (d) GFRP bar loaded at 60% of the UTS at low magnification; (e) GFRP bar loaded at 80% of the UTS at low magnification; and (f) GFRP bar loaded at 80% of the UTS at high magnification

of 80% of the UTS [Fig. 10(c)], and specimen aged by traditional aging in alkaline solution at 60°C [Fig. 10(c)]. The visual and microstructural observations of preloaded bars embedded in mortar showed no significant damage, except the presence of cracks in fibers due to the preloading, after 240 days of immersion in the tap water at the highest temperature (50°C). The comparison of Figs. 10(c and d) shows that there was no significant damage occurred to preloaded mortar-wrapped GFRP bar [Fig. 10(c)] whereas the damage was clear on the bar aged in alkaline solution [Fig. 10(d)]. Observation of these interfaces and of the microstructure, in general, demonstrates that the conditionings of preloaded mortar-wrapped bars in water do not affect the microstructural properties of the GFRP bars.

Summary and Conclusions

Based on the results of this study the following conclusions may be drawn:

1. High stress level (more than 60% of the UTS) leads to fiber cracking, resulting in an increase in moisture uptake at saturation and a decrease in GFRP density related to the higher void content.
2. Short-term tensile properties are not affected by the preloading. Even if some fibers are broken the tensile strength and elastic modulus are unaffected.
3. After 240 days of water immersion of preloaded bar embedded in mortar, the retention rates of tensile strength are 95, 96, and 98% at 50, 40, and 23°C, respectively.

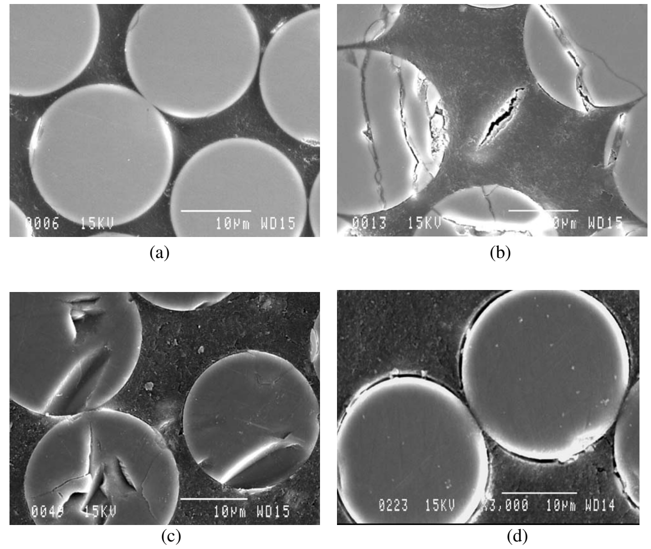

Fig. 10. Micrograph of transversal GFRP bar surface: (a) reference GFRP bar; (b) GFRP bar preloaded at 80% of the UTS; (c) GFRP bar preloaded at 80% of the UTS and embedded in moist mortar during 240 days at 50°C; and (d) GFRP bar aged in alkaline solution at 60°C

4. No significant microstructural changes were observed after 240 days of immersion of GFRP bars embedded in mortar in tap water at 50°C after a preloading of 80% of the UTS. The interface between the resin and the fibers did not seem to be affected by the moisture absorption and high temperatures.
5. FTIR did not show any nonreversible degradation of the polymer chemical structure, i.e., hydrolysis. On the other hand, DSC scans showed a slight decrease in the T_g for aged sample which corresponded to reversible physical interaction between the water and the polymer matrix, i.e., plasticization. Further study may be focused on this aspect.

From these observations, it can be concluded that the short- (after preloading) and long-term (after conditioning of preloaded bars) behaviors of GFRP bars subjected to high stress level (80% of the UTS) and to aggressive environment are not affected. The presence of fiber cracking does not seem to affect the mechanical properties even after 240 days at 50°C, which represented the harsher conditioning used in the present study.

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