MECHANICAL, PHYSICAL AND DURABILITY CHARACTERIZATION OF PRE-STRESSED GFRP REINFORCING BARS

M. Robert 1, B. Benmokrane 1
1 Department of Civil Engineering, University of Sherbrooke, Quebec, Canada

ABSTRACT

This paper presents the physical and durability characterization of glass fibre-reinforced polymers (GFRP) bars subjected to different tensile stress levels. GFRP bars were first loaded at levels up to 20, 40, 60 and 80 % of their ultimate tensile strength (UTS) to simulate the effect of an impact collision which can create cracks and microcracks in the FRP bars and affect the long-term durability of the product. The experimental 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 (80 % UTS approx) was in place.

KEYWORDS

GFRP, reinforcing bar, pre-tensioned, cracking, durability.

INTRODUCTION

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 majority of this research has highlighted on the short-term performance of FRP reinforced concrete structures or on the durability of FRP reinforcing bars subjected to ageing in alkaline solution. Barely any research is reported on the durability of FRP bars embedded in moist concrete which simulate the real conditions of application, and on the adverse effects of the presence of cracks and microcracks in the FRP bars on their long-term durability.

It is recognized that FRP bars, especially GFRP bars, are susceptible to attack under exposures to moisture, alkaline solutions and elevated temperature [Chen et al. 2006, 2007]. 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 presence of cracks and microcracks in the bar itself can significantly affect the long-term durability of GFRP reinforcing bars.

The short and long-term properties of GFRP bars subjected to high stress level were investigated in the present study. Microstructural observations were conducted to show the deterioration of fibre, matrix and the fibre/matrix interface after pre-loading. Moisture absorption of loaded GFRP bars was measured at different temperatures to estimate the potential effects of the presence of cracks on durability-related properties. Loaded bars were also embedded in a moist concrete at elevated temperature to perform accelerated ageing. The measured tensile strengths of the bars before and after exposure were considered as a measure of the durability performance of the specimens.

EXPERIMENTAL PROGRAM

Materials

Sand coated glass FRP bars manufactured by a Canadian company were used in this study. The bars were made of continuous E glass fibres impregnated in a vinylester resin using the pultrusion process. The mass fraction of glass was 81.5 % and was determined by thermogravimetric analysis according to ASTM E 1131 standard. Their relative density according to ASTM D 792 standard was 1.99. GFRP bars had a nominal diameter of 12.7 mm. Samples were preloaded by tensile test prior to mechanical and physical characterization to simulate the effects of impact loading and to initiate the creation of cracks in polymer. All bars prepared for tensile preloading were cut of length equal to 1440 mm as specified by the ACI 440.3R-04 B2. The bars were divided into three series;
1) the unconditioned reference samples; 2) the unconditioned preloaded samples without concrete cover, and 3) the conditioned samples (60 bars) embedded in concrete and preloaded. The mortar mixture consisted of 3 parts of sand, 1 part of type I cement according to ASTM C 150 standard and a water/cement ratio of 0.40 which led to a concrete pH of 12.15 measured by the extraction of the interstitial solution after aging. The concrete (or mortar) was cast only in the middle third of the bars to avoid any degradation at the ends which were used as grips during the tensile tests. The concrete mold of the envelope was made of wood having a square section of 48 mm that gave a minimum concrete cover of 18 mm. Figure 1 shows a picture of a mortar-wrapped bar.

![Figure 1. View of cement mortar-wrapped GFRP bar specimen](image)

**Preloading of GFRP bars**

Before aging, GFRP bars were preloaded at four different stress levels: 20, 40, 60 and 60 % of their theoretical ultimate tensile strength (788 MPa) (UTS). All bars were preloaded under tension according to the ACI 440.3R-04 B2. The test was carried out using a MTS 810 machine and the load was increased until desired load level was reached. For each tensile preloading, the specimen was mounted on the press with the steel pipe anchors gripped by the wedges of the upper and the lower jaw of the machine. The rate of loading ranged between 250 and 500 MPa/min and the maximum load was maintained for 10 minutes after that the load was removed at a rate of deloading between 250 and 500 MPa/min.

**Moisture Uptake**

After the preloading of GFRP bars, moisture uptake measurements at saturation were made by immersing a few preloaded specimens without concrete cover in tap water during one month at 50°C, removing some specimens from their solutions, wiping them dry and measuring their weight immediately, according with ASTM D570 standard. The percentage moisture uptake was calculated with Eq. 1, where \(\%M\) is the mass gain due to moisture uptake, \(M_{\text{cond}}\) is the mass of the specimen after its conditioning and \(M_{\text{dry}}\) is the mass of the specimen before its conditioning. 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 specimens that were immersed and by comparing their ensuing mass to their initial mass. Eqs. 2 and 3 were used to determine the mass loss after immersion and corrected mass gain of pre-loaded specimens, respectively. In those equations, \(\%M_{\text{loss}}\) is the mass loss of the specimen after conditioning due to various dissolution phenomenon, \(M_{\text{redry}}\) is the mass of the specimen completely dried after conditioning and \(\%M_{\text{corr}}\) is the corrected mass gain due to moisture uptake.

\[
\%M = \frac{100(M_{\text{cond}} - M_{\text{dry}})}{M_{\text{dry}}} \quad (1)
\]

\[
\%M_{\text{loss}} = \frac{100(M_{\text{redry}} - M_{\text{dry}})}{M_{\text{dry}}} \quad (2)
\]

\[
\%M_{\text{corr}} = \%M - \%M_{\text{loss}} \quad (3)
\]

**Tensile Strength Retention**

After conditioning, all bars were tested under tension according to the ACI 440.3R-04 B2 standard and using the same parameter used in preloading procedure. Reference samples and samples preloaded at 80% of the UTS, which represented the harsher conditioning, the results of those were compared to measure the effect of a potentially high stress level on the short-term mechanical properties of GFRP bars. Also, long-term durability of
preloaded samples was estimated by testing the embedded samples aged in water at different times of immersion. Each specimen was instrumented with a Linear Variable Differential Transformer (LVDT) to capture the elongation during testing. The test was carried out using a MTS 810 machine and the load was increased until failure. The applied load and bar elongations were recorded during the test using data acquisition system monitored by a computer.

Microstructural Observation

SEM observations and image analysis were also performed to observe the microstructure of specimens before and after preloading. Samples observed in the SEM were the unconditioned specimens, specimens prestressed at a level of load of 20, 40, 60 and 80 % of the ultimate tensile strength (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 vapour-deposit process. After the 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 fibres or interfaces, if any.

Long-Term Durability

After preloading, 60 bars preloaded at 80% of the UTS were embedded in mortar and subjected to different agings. Accelerated aging of preloaded GFRP reinforcing bars embedded in concrete was achieved by using a method in the study which designed to simulate an aggressive alkaline environment of saturated concrete. The embedded samples were immersed in tap water which differed from the conventional accelerated aging tests where bare bars are directly immersed in alkaline solutions simulating the aforementioned resulting. The technique currently used was believed to be 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 concrete, thus allowing the liberation of the alkaline ions of the concrete directly in the environment of bars. The aging was performed by immersing the mortar-wrapped GFRP bars in a wood container specially manufactured for the study. Figure 2 shows the containers that were tightly closed with a polyethylene film on their inner surfaces. A polyethylene sheet was also placed on top of the wood containers to avoid excessive evaporation of water during the conditioning. Bars were spaced from each other and from the bottom of the container to allow the free circulation of the solution between and around the GFRP bars. Furthermore, the water level was kept constant throughout the study to avoid a pH increase which could be due to a water level decrease and a significant increase of the 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) and were removed from the water after 120 days. Two other periods of time (240, and 365 days) also would be investigated in other publication [Robert and Benmokrane 2009]. After period of immersion, six GFRP bars were removed from the water and tested under tension to compare their tensile strength retention values to those of the reference specimens. No significant change was observed at the surface of GFRP bars after the immersion.
EXPERIMENTAL RESULTS

Moisture Absorption

Figure 3 shows mass uptake by different specimen due to tap water absorption. It was seen that higher the load level, the greater the mass uptake. 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. The increase in moisture uptake could be due to the damage caused by the preloading to sample microstructure. It could be expected that higher the load level greater the presence of cracks and micro cracks induced by the stress. Moisture penetration into composite materials could be by three different mechanisms: 1) diffusion of water molecules inside the micro-gaps between polymer chains, 2) capillary transport into the gaps and flaws at the interfaces between fibres and polymer and 3) transport by micro-cracks in the matrix, formed during the 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. Furthermore, it was seen that the moisture uptake increase was more quickly between a load level of 60 and 80% of the UTS compared between 0 and 60% of the UTS. So, it was concluded that the major part of the micro structural damage occurred at very high load level around 80% of the UTS. The highest specimen mass loss 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.

![Figure 3. Mass uptake of reference and pre-loaded GFRP bar specimen](image)

Tensile Properties after Pre-Loading

The tensile test of reference and pre-loaded specimens showed an approximately linear behavior up to failure. Specimens failed by the rupture of fibers. The failure was accompanied by the delamination of fibers and resin. Micelli and Nanni (2004) also observed similar tensile failure modes of GFRP bars. Table 1 shows the ultimate tensile strength and Young’s modulus of reference bars and of bar subjected to a 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 the high stress level (80% of the UTS) used for their preloading. These results showed that tensile properties of GFRP bars just after the application of a high stress level, leading to the creation of cracks and microcracks, were not affected by their preloading at 80% of their UTS.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile Strength (MPa)</th>
<th>COV (%)</th>
<th>Young Modulus (GPa)</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>854</td>
<td>4</td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td>80% UTS</td>
<td>851</td>
<td>3</td>
<td>43</td>
<td>3</td>
</tr>
</tbody>
</table>
Long-Term Tensile Properties

Table 2 shows the experimental results obtained during the tensile tests concerning the ultimate strength and the modulus of elasticity of reference and pre-loaded (80% UTS) bars tested after 120 days immersion in water at different temperatures.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile Strength (MPa)</th>
<th>COV (%)</th>
<th>Young Modulus (GPa)</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>854</td>
<td>4</td>
<td>43</td>
<td>1</td>
</tr>
<tr>
<td>120 days-23°C</td>
<td>836</td>
<td>5</td>
<td>42</td>
<td>4</td>
</tr>
<tr>
<td>120 days-40°C</td>
<td>823</td>
<td>7</td>
<td>43</td>
<td>3</td>
</tr>
<tr>
<td>120 days-50°C</td>
<td>808</td>
<td>3</td>
<td>44</td>
<td>6</td>
</tr>
</tbody>
</table>

Results presented in Table 2 show a slight decrease (2 to 5%) of the ultimate tensile strength after 120 days of immersion of pre-loaded bars embedded in concrete. This decrease was similar to the loss of tensile strength measured by Robert et al. (2009b) on same bar subjected to same conditionings but without preloading. From this observation, it could be concluded that the preloading of GFRP bars, and the presence of microcracks in the bar microstructure, doesn’t 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 resistance. It was seen that for duration of immersion of 120 days, the loss of resistance is equal to 2, 4 and 5 % at 23°, 40° and 50°C, respectively. This phenomenon was due to the increasing of the diffusion rate of the solution inside the sample and to the acceleration of the chemicals reaction of degradation with the temperature of immersion, leading to a larger absorption rate of the solution for the same time of immersion and accelerated reaction of degradation. The absorption of solution could lead to a degradation of the fibres and fibre/matrix interface, leading to a loss of the ultimate tensile.

Concerning the stiffness of embedded pre-loaded GFRP bars after aging in that water, it was seen from the measured results presented in Table 2 that after 120 days, the loss of elastic modulus was negligible and all aged bars were not affected by the higher temperature or the exposure to moist concrete. This result shows 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. (2009b) on same bars subjected to same aging but without pre-loading.

Microstructural Effects

The micrographs of Figure 4 show the longitudinal bar surface of reference and pre-loaded GFRP bar. In particular, the fibres and the interface between the fibres and the resin should be observed. Observations of these interfaces and of the microstructure in general demonstrated that the pre-loading affects the microstructure of GFRP bar. In fact, 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 fibres and the polymer matrix, even under stress of 80% of the UTS. The only visible damage occurred at the fibre level since the elongation at the rupture was lower for the fibres compared to the polymer matrix. It was also seen that no micro structural change was observed for preloading level less than 60% of the UTS. For these low stress levels, the elongations of fibres and matrix were possible. For stress level higher than 60%, the fibres began to break. These observations were in accordance with moisture uptake and density measurements in the way that the increase of microcracking at high stress levels leads to an increase of moisture uptake and a decrease of density.

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 fibre cracking, resulting in an increase of moisture uptake at saturation and a decrease of GFRP density related to the higher void content.
(2) Short-term tensile properties are not affected by the pre-loading. Even if some fibres are broken the tensile strength and elastic modulus are unaffected.
(3) After 120 days water immersion of pre-loaded bar embedded in concrete, the retention rate of tensile strength are 95, 96 and 98% at 50, 40, and 23°C, respectively.

From these observations, it can be concluded that the short- and long-term behavior of GFRP bars subjected to high stress level and to aggressive environment are not affected. The presence of fibre cracking doesn’t seem to affect the mechanical properties even after 120 days at 50°C. This ongoing study will further give more information about the long-term durability of pre-loaded GFRP bars.
Figure 4. Micrograph of longitudinal GFRP bar surface pre-loaded under tensile load

ACKNOWLEDGEMENT

This research was supported by the National Science and Engineering Research Council (NSERC) of Canada and the Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada).

REFERENCES


