Study of the performance of FRP reinforcing bars subjected to extreme conditions of application

Mathieu Robert [1] — Patrice Cousin [2] — Brahim Benmokrane[3]

ABSTRACT. Fiber-reinforced polymer (FRP) materials have emerged as a practical alternative material for producing reinforcing bars for concrete structures. This is due to their relatively low cost-to-performance ratio and noncorrosive nature compared to traditionnal steel reinforcing bars. In addition, FRP materials exhibit properties, such as high tensile strength, that 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. Moisture, high pH of surrounding environment, extreme temperature and the presence of microcracks can affect the long-term properties of FRP reinforcing bars. This paper summarizes the long-term durability study of glass fibre-reinforced polymer (GFRP) reinforcing bars subjected to different conditionnings simulating the real environment of application. In particular, the behavior of GFRP bars subjected moisture, high pH of moist concrete, extreme temperatures, and to tensile prestress was investigated showing the great durability of GFRP reinforcing bars.

KEYWORDS: FRP, composites materials, reinforcement, concrete, high temperature, absorption, mechanical properties, rate of reaction, prediction model.

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1. Introduction

Many steel reinforced concrete infrastructures exposed to harsh environments present durability issues and are likely not to reach the lifetime expected or have already attained the service limit. Steel corrosion induced by chlorides and/or carbonation are the main causes of deterioration of steel reinforced concrete structures. The amplitude of the phenomenon and economic factors have pushed research engineers, industries and public institutions to develop new technologies to better protect reinforcing steel or providing non corrosive materials in replacement of steel [1]. In anticipation of offering an alternative material, research works have been conducted to develop and use fibre reinforced polymer (FRP) composites in civil engineering applications.

A composite material may be defined as a material constituted of at least two dissimilar materials providing complementary properties, which offers a better general performance than each of its components [2]. FRP composite materials are composed of reinforcing fibres embedded and protected by a polymeric resin matrix. The main fibres used for civil engineering applications are glass, carbon and aramid fibres. Glass fibre being the main fibre used because of its good properties, high strength/cost ratio, good usability and excellent availability. Mechanical properties of glass fibre reinforced polimer reinforcements depend on the characteristics, orientation and shape of fibre, fibre/matrix volumetric ratio, the bonding at the interface between fibres and matrix and on the manufacturing processing. The function of the resin matrix is to keep the fibres in place, transfer and distribute stresses through fibres, bring a lateral support against buckling under compression and protect fibres from abrasion and surrounding environment. Because of their high chemical resistance, vinylester-based resin is generally used for civil engineering applications [3]. This article deals with the FRP reinforcing bars for concrete structures (figure 1). Several concrete structures using FRP as structural internal reinforcement have been built in North America and worldwide. Also, several design codes and guides dealing with composite material as reinforcement for concrete structures have been developed [4-7]. Also, codes and guides on specification, construction, and certification of FRP reinforcing bars for concrete structures has been issued [8-10].

Figure 1 GFRP reinforcing bars

One of the biggest challenges for the acceptance of FRP in civil engineering applications concerns their durability and more specifically their capacity to maintain their structural performance in severe and changing environmental conditions of service [11]. The durability of FRP reinforcing rods is related to the three different phases of the material: fibre, resin and interface (figure 2), which may be affected by deteriorations and degradations caused by exposure to various environments and could potentially lead to a reduction of long term durability and performance.

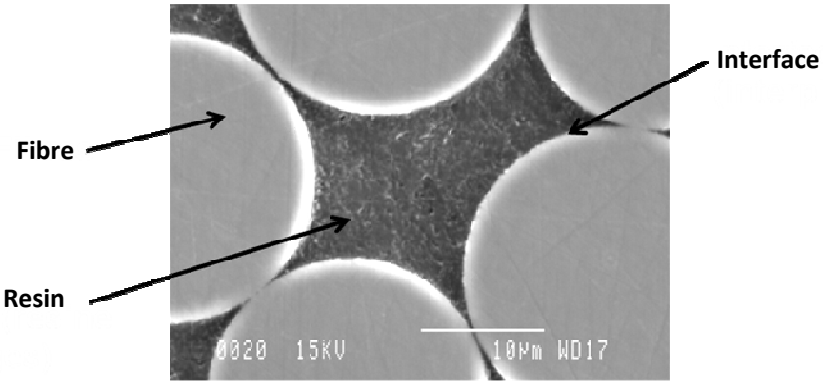


Figure 2 Typical microstructure of GFRP bar

The polymeric component of FRP materials protects fibres against the chemical attack of corrosive ions, especially hydroxyl ions, present in the pore water of the surrounding concrete. The degradation process of GFRP reinforcing bars may be caused by the deterioration of one (or more) of its phase: fibre, resin matrix or interface. The degradation mechanisms are more complex compared to those occurring in a monophasic material, such as steel.

Mechanical properties of GFRP bars are controlled by the fibre component [12]. Once the fibres are not deteriorated, the material will keep most of its mechanical strength and will be able to support the loads. If the protective resin degrades, the fibres located in the outer part of the bar will rupture and the bar resistance will start to decrease. According to Uomoto's work [13], the interface between the glass fibre and resin controls the chemical resistance of GFRP against alkaline corrosion. The increase of the bonding degree at the interface may highly improve the chemical resistance of these materials. Many studies dealing with the resistance of GFRP to alkalis have shown that the alkaline environment of concrete is among the most critical environments for glass fibre [14]. Actually, the main issue is the potential degradation caused by the concrete pore solution, the pH of which may reach 13.5. In alkaline environments, glass fibre may degrade according to several mechanisms, such as corrosion, hydrolysis and leaching. Several studies on the corrosion mechanisms of GFRP reinforcing bars and environmental effects have been published [15-20]. Yilmaz and Glasser [15] describe fibre glass attack by the dissolution of silica (SiO_2) by alkaline ionic species (hydroxyl groups) according to equation (1). In this equation, the first by-product, SiOH, forms a gel on the glass fibre surface, whereas the second one, SiO^-, is dissolved.

$$\left[-\overset{|}{\underset{|}{Si}}-O-\overset{|}{\underset{|}{Si}}\right]+OH^- \rightarrow 2-\overset{|}{\underset{|}{Si}}-OH(solid)+\overset{|}{\underset{|}{Si}}-O^-(solution) \qquad (1)$$

This dissolution can cause a weight loss and a diameter decrease of the glass fibre, reducing the mechanical properties of the bar. Another mechanism of degradation, resulting from the reaction of silica with the alkaline environment, is the formation of calcium silicate expressed in the equation (2) [18].

$$Ca(OH)_2 + SiO_2 \rightarrow CaSiO_3 + H_2O \qquad (2)$$

Different studies have shown that alkaline environments are more critical than water at the beginning of the degradation but become almost similar later [21]. The mechanisms of fibre degradation by water were discussed by Mercier and Maréchal [22]. They have reported that immersion of glass fibres in water can lead to their dissolution through the diffusion of hydroxide ions outside the glass fibres, called lixiviation. This lixiviation is exacerbated by the amount of alkalis present inside the glass fibres and the temperature of the wet environment. After lixiviation, the formation of large amounts of hydroxides leads to an increase of the pH of the solution. Then, these hydroxide ions attack the fibre surface, leading to the formation of cracks and microcracks, which decrease the resistance and can result in a premature fracture of glass fibres [23-24].

The diffusion of moisture and alkalis from the concrete into the polymer matrix can lead to changes in the mechanical, thermomechanical and physico-chemical properties of GFRP reinforcing bars. The main effect of the absorption is the possible degradation of the polymer resin through hydrolysis or plasticizing effects. The chemical resistance of thermoset resins is largely governed by the chemical nature of the polymer chain. Weak adhesion of the polyester resin can result in serious deterioration when hydroxyl ions penetrate into the structure. 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 could further damage the matrix. Meanwhile, the matrix formed by vinylester, which contents much less ester units as compared to polyester, is also hardly deteriorated by hydroxyl ions compared to a polyester matrix [19, 24, 25].

The interface (or interphase) is a heterogeneous region of some micrometers in thickness between the matrix and fibres. This interface plays a critical role as it insures the load transfer between the fibres and matrix [24, 26]. The application of a coupling agent (silane) at the surface of the fibres improves the bonding at the interface and protects the fibre surface against environmental attacks. However, this chemical bond is not stable in presence of humidity and alkalis and it is particularly subjected to long-term degradation [24, 26]. When moisture and alkali ions diffuse through the composite, this bonding is gradually reduced, leading to the deterioration of the interface. The resistance of this interface is directly related to the amount of coupling agent which cannot be extracted from the fibre surface.

A high level of sustained load combined with chemical attacks, increases the degradation of the interface. Different types of damage may be observed: (1) osmotic cracking of the matrix, (2) differential swelling and (3) delamination of the fibres.

The extensive research performed on FRP reinforcements led to the publication of codes and design guides on the use of the FRP reinforcing bars and prestressing tendons as reinforcement for new or existing concrete structures. Design codes and guides in North-America and Japan [4-7] provide strength reduction factors or material factors to account for the effects of environmental conditions, creep under sustained loads, and fatigue under repeated loads. The use of an environmental reduction factor (C_E) was a simple solution to overcome the difficulties caused by the absence of data on the long-term durability of FRP's. Several codes require an environmental reduction coefficient of approximately 0.7. This factor mitigates the use of new generation of FRP products, which are less vulnerable to environmental attacks than the previous products. These environmental reduction coefficients are considered to be very conservative and are being criticized by many experts and engineers, because they are based on the behaviour of the early generations of FRP products that were of lower quality and on limited long-term behaviour data.

This paper presents an overview of several aspects affecting the long-term durability of GFRP reinforcing bars subjected to laboratory accelerated aging simulating the genuine environment of application. The durability of GFRP bars submitted to various environmental conditions such as wet concrete, extreme temperatures and microcracks-inducing pre-loading will be evaluated though the residual mechanical properties.

2. Experimental Program

2.1 Material

Experimental results presented in this paper were obtained during research work conducted in the laboratory of durability of FRP composite materials of the department of civil engineering of the University of Sherbrooke, Sherbrooke, Canada. Sand-coated glass FRP reinforcing bars manufactured by a Canadian company (Pultrall inc., Thetford Mines, Quebec, Canada) are used in this study (Figure 1). The bars are made of continuous E-glass fibres embedded in vinylester matrix using a pultrusion process. The GFRP bars used have a nominal diameter of 12 mm.

2.2 Test Plan

2.2.1 Aging in Moist Concrete

Accelerated aging of GFRP reinforcing bars embedded in concrete, used in this study, were designed to simulate an aggressive alkaline environment of saturated concrete. The embedded samples were immersed in tap water. The technique currently used is believed to be representative of the real life situation. Indeed, the pH of the solution surrounding the bars is a result of the absorption of water by the concrete, thus allowing the liberation of the alkaline ions of the concrete directly in the bars environment. The aging was performed by immersing the mortar-wrapped GFRP bars in a wood container specially manufactured for the study. Figure 3 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^{o}C) and were removed from the water after four different periods of time (60, 120, 180 and 240 days). After each period, usually six GFRP bars were removed from the water, tested under tension to compare their tensile strength retention values to those of the reference specimens. Microstructural and physical analysis were also performed after immersion.

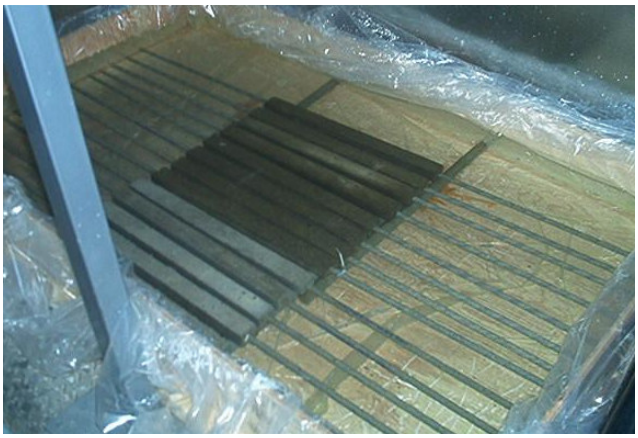


Figure 3 Wood container built for aging of the cement mortar-wrapped GFRP bar specimens

2.2.2 Extreme Temperatures

Properties of GFRP bars submitted to extreme temperatures were measured. All GFRP bar specimens were tested under extreme temperature conditions using a MTS environmental chamber cooled by liquid nitrogen (Figure 2). Sub-zero temperatures equal to -100^{o}, -80^{o}, -60^{o}, -40^{o}, -20^{o} and also 0^{o}C were chosen to simulate the effect of Nordic climate on GFRP bars. The temperatures below -60 ^{o}C were used to amplify the effects of temperature on mechanical and microstructural behaviour of the FRP materials. Elevated temperatures equal to 50^{o}, 100^{o}, 150^{o}, 200^{o}, 250^{o} and 325^{o}C were chosen to simulate short-term environmental conditions in the case of fire. All the tests were conducted using a steady-state temperature (heat then load) regime. To be sure that the temperature at the core of the GFRP bars reached the desired temperature, an extra GFRP bar was kept in the same conditions and its core temperature was monitored using a thermocouple that was inserted in the core of this bar. When the desired temperature was reached (from the thermocouple reading), it was kept constant and the GFRP specimens were tested at that temperature.

Figure 4 Test setup for tensile tests at controlled temperature

2.2.3 Pre-Loading of GFRP Bars Samples

The effect of cracking and microcracking on the long-term behaviour of GFRP bars was evaluated. GFRP bars were preloaded at 80 percent of their theoretical ultimate tensile strength (854 MPa) (UTS) to initiate cracks and microcracks in polymer and glass fibres. All bars were preloaded under tension according to ASTM D 7205 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 minutes, and then was reduced at the rate of 250 to 500 MPa/min. The study of the long-term behaviour of pre-loaded GFRP bars was performed by using accelerated aging in moist moist concrete, as described above.

2.3 Mechanical Characterization

Tensile tests were performed on bars aged in solution, bars subjected to controlled temperatures and bars pre-loaded at 80 percent of their UTS. The measured tensile strengths of the bars before and after exposure were considered as a measure of the durability performance of the specimens. All bars were tested under tension according to the ACI 440.3R-04 B2. Each specimen was instrumented with a Linear Variable Differential Transformer (LVDT) to capture the elongation during testing. The test was carried out using a Baldwin testing machine and the load was increased until failure. For each tensile test, 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. Just before the test, the concrete cover was carefully removed from the middle third of the specimens with a hammer to avoid any damage to the bar. The rate of loading ranged between 250 and 500 MPa/min. The applied load and bar elongation were recorded during the test using a data acquisition system monitored by a computer. Due to the brittle nature of GFRP, no yielding occurs and the stress-strain behaviour was linear.

2.4 Physical Characterization

2.4.1 Density Measurements after Pre-Loading

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 (3 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 the equation Eq. 3.

$$\rho = Ps / Ps + Pw + Ps + w \quad (3)$$

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

2.4.2 Scanning Electron Microscopy (SEM)

SEM observations and image analysis were performed to evaluate the microstructure of aged specimens and the integrity of the GFRP material after exposure to extreme temperatures. All specimens were first cut, polished and coated with a thin layer of gold–palladium by a vapor-deposit process for observing in the SEM. Microstructural observations were thereafter performed on a JEOL JSM-840A SEM. These observations were conducted to determine the potential degradation of the polymer matrix, possible glass fibers and interface.

2.4.3 Differential Scanning Calorimetry (DSC)

DSC was used to obtain information on the thermal behavior and characteristics of polymeric materials and composites such as glass transition temperature (Tg), melting point, curing process, crystallinity, thermal stability, and relaxation. In the study, specimens weighting 12 to 15 milligrams were cut from different GFRP samples (non-conditioned and conditioned) and placed in aluminum pans and were analyzed using a TA Instruments DSC Q10 calorimeter. Specimens were heated from 25°C to 195°C at a rate of 5°C/min. Glass transition temperature was determined for both the specimens in accordance with ASTM E 1356 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.

2.4.4 Dynamical Mechanical Analysis (DMA)

DMA was used to determine changes in the mechanical properties of FRP composite materials either under isothermal conditions or as a function of temperature. Glass transition temperature, stiffness, and damping properties could also be measured by this technique. Dynamic mechanical testing provided a method to determine elastic and loss moduli of materials and could be used to evaluate and compare composite parameters, such as adhesion and interface properties, some of the processing treatments, curing, and stress state. In the present study, some GFRP bar specimens were tested by DMA under flexure to measure the effect of temperature on the flexural modulus of elasticity for temperatures ranging from -100° to 350°C. The tests were carried out according to ASTM D 5023 standard and using a TA Instruments DMA Q800 testing machine equipped with a three point bending device. The span between the supports was kept equal to 50 mm. The rate of loading is chosen to allow a deflection of 10 microns.

2.4.5 Thermogravimetric Analysis (TGA)

TGA determined the changes in weight of FRP composites as a function of temperature. The TGA could be used to calculate glass fibre and moisture contents and to study the thermal stability of matrix. In the study, the thermal stability of specimens was investigated by using

TGA, and the weight loss traces were recorded as function of temperature in the range of 20–800 °C according to ASTM E 1868 standard. The mass variations recorded could give indications concerning the different phenomena of degradation occurring in the matrix and also explain the loss of mechanical properties observed at very high temperatures. Thermogravimetric analysis was carried out by using TA Instrument Q500 TGA equipment under air with a heating rate of 20 °C min^{-1}.

3. Experimental Results

3.1 Effect of Immersion

3.1.1 Tensile Strength Retention

Table 1 shows the experimental results obtained during the tensile tests concerning the ultimate strength of aged bars tested after immersion. Figure 5 shows the retention of the ultimate strength of aged bars according to the duration of immersion of embedded bars at various temperatures. As shown in Table 1, the tensile strength for unconditioned bar was equal to 788 ± 54 MPa. Note that the tensile strength of bars was reduced to 665 ± 62 MPa after 240 days exposure to water at 50 °C.

Figure 5 shows a slight decrease of the ultimate tensile strength with immersion duration. The recorded results show that the longer the time of immersion, the larger the loss of resistance. Furthermore, it is clear that the temperature of immersion affects the loss of resistance. It can be seen that for duration of immersion of 8 months, the loss of resistance is equal to 16, 10 and 9 % at 50°, 40° and 23°C, respectively. This phenomenon is due to the increasing of the diffusion rate of the solution 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 can lead to a degradation of the fibres and fibre/matrix interface, leading to a loss of the ultimate tensile.

Table 1 Experimental tensile strength of reference specimens and specimens aged in moist concrete

Time of immersion (days)	Temperature (°C)	Mean Tensile Strength (MPa)	COV (%)
0	23	788	6,9
60	23	753	8,2
	40	755	3,7
	50	767	3,8
120	23	702	2,0
	40	666	7,8
	50	720	3,2
180	23	717	2,6
	40	708	4,8
	50	711	2,5
240	23	714	3,5
	40	708	7,1
	50	665	9,3

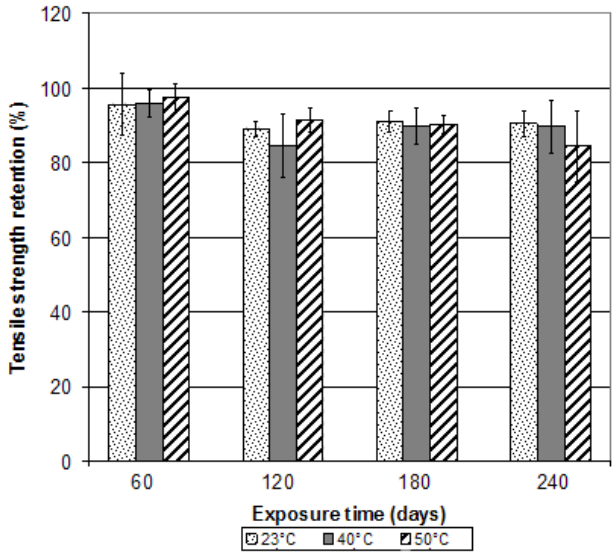


Figure 5 Tensile strength retention of conditioned GFRP bars aged in moist concrete at 23°, 40°, and 50 °C

Figure 6 shows the change in the elastic modulus of aged bars with time of immersion at various temperatures. Indeed, it can be seen from the measured results that after 240 days, the loss of elastic modulus is negligible and all aged bars are not affected by the higher temperature or the exposure to moist concrete. This result shows that elastic modulus of bars is not affected by aging in concrete environment.

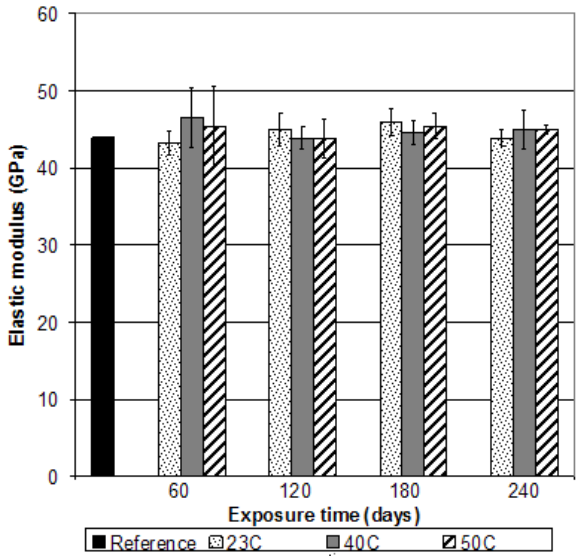


Figure 6 Elastic modulus retention of conditioned GFRP bars aged in moist concrete at 23°, 40°, and 50 °C

3.1.2 Change in Density

Table 2 shows the measured density for reference sample and samples preloaded at 80 percent of the UTS. As expected, higher the load level, lower the density. In fact, a loss of 15 percent of the density was measured after pre-loading of the GFRP bar specimen at 80 percent of the UTS. This result could be explained due to the creation of cracks and microcracks by preloading of GFRP bars. Matrix cracking and debonding at fibre/matrix interface cause an increase of void content of the GFRP bar and decrease in the measured density. This result was in accordance with microstructural observations performed by SEM (Figure 8).

Table 2 Experimental density measured before and after pre-loading of GFRP bars

Condition	Measured Density	COV (%)
Reference	2,12	2.1
Pre-loaded at 80% of the UTS	1,81	1.8

3.1.3 Effect on Tensile Properties of Pre-Loaded Bars

Table 3 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 60, 120, 180 and 240 days of immersion in water at different temperatures.

Table 3 Experimental tensile strength of reference specimens and pre-loaded specimens aged in moist concrete

Time of immersion (days)	Temperature (^{o}C)	Mean Tensile Strength (MPa)	COV (%)	Mean Modulus of Elasticity (GPa)	COV (%)
0	23	854	2	43	2
60	23	846	5	44	3
	40	847	6	43	3
	50	838	4	43	4
120	23	849	2	42	5
	40	832	8	43	4
	50	837	3	44	2
180	23	836	3	42	4
	40	823	5	43	6
	50	808	3	41	4
240	23	810	4	43	3
	40	784	7	42	2
	50	768	9	43	2

Results presented in Table 3 show slight decrease (6 to 11%) of the ultimate tensile strength after 240 days of immersion of pre-loaded bars embedded in mortar. This decrease was similar to the loss of tensile strength measured on same bar subjected to same conditionings but without preloading. This phenomenon was due to the increasing of diffusion rate of the solution into the sample due to the presence of cracks and microcracks 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 higher absorption of solution could lead to a higher 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 the water, it was seen from the measured results presented in Table 3 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 testing similar bars subjected to same aging but without pre-loading.

3.1.4 Effect on Failure Mode

The tensile test of unconditioned specimens, specimens aged in moist concrete at 50°C during 240 days and pre-loaded specimens aged in moist concrete at 50°C during 240 days showed an approximately linear behaviour up to failure. Specimens failed through the rupture of fibres. The failure was accompanied by the delamination of fibres and resin, as shown in Figure 7. From this observation, it could be concluded that the aging in moist concrete or the presence of pre-existing cracks and microcracks due to the pre-loading of bars, have no significant effects on the failure mode occurring during tensile tests.

3.1.5 Microstructural Effect of Pre-Loading

The micrographs of Figure 8 show the longitudinal bar surface of reference and GFRP bar pre-loaded at 80 percent of the UTS. 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 affected the microstructure of GFRP bar. 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. No damage occurred at the matrix and fibre/matrix interface, even at very high stress level (up to 80 percent of the UTS). These observations were in accordance density measurements in the way that the increase of microcracking at high stress levels leads to a decrease of density.

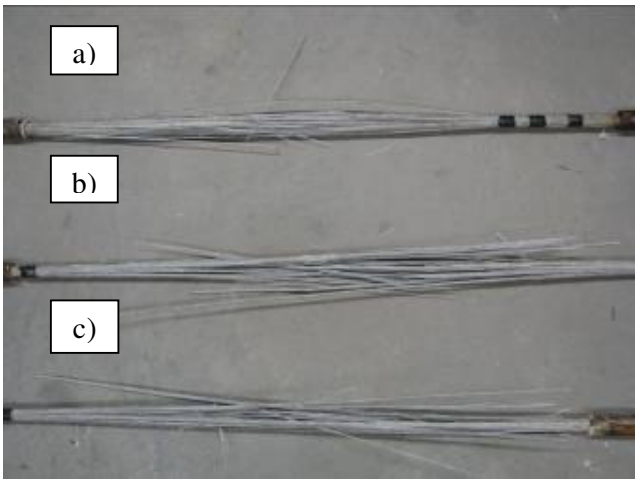
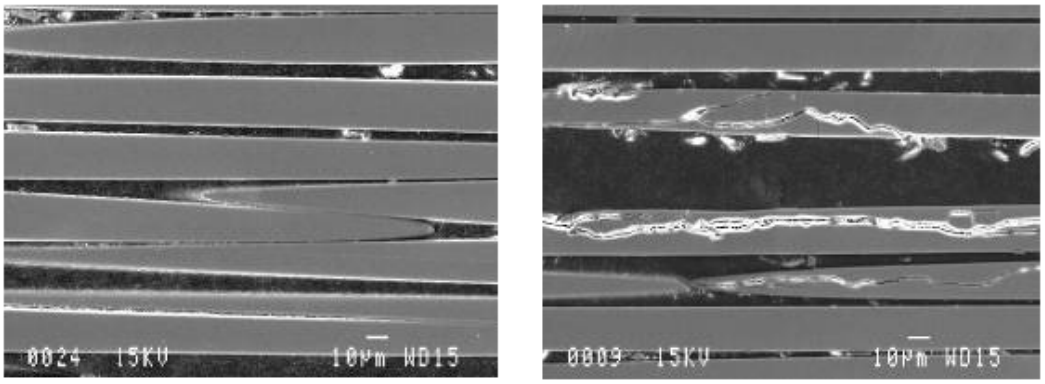


Figure 7 Typical failure mode for GFRP bars: a) reference, b) bar aged in moist concrete at 50°C during 240 days, c) bar pre-loaded at 80% of the UTS and aged in moist concrete at 50°C during 240 days.

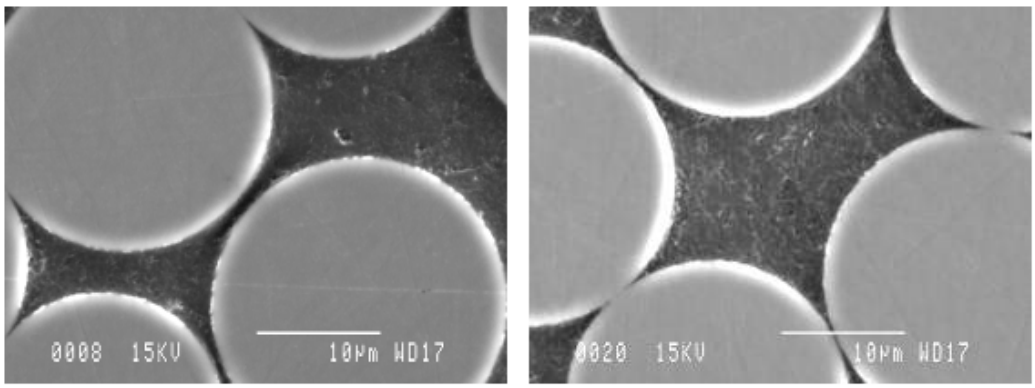


(a) (b)

Figure 8 Micrograph of longitudinal GFRP bar surface pre-loaded under tensile load: a) Reference GFRP bar at low magnification, and b) GFRP bar loaded at 80% of the UTS at high magnification

3.1.6 Microstructural Effect of Aging in Moist Concrete

The visual and microstructural observations of reference and pre-loaded bars showed no significant damage after 240 days of immersion in the tap water at the highest temperature (50°C). The micrographs of Figure 9 show the fibres/matrix interface for reference and pre-loaded bars aged in moist concrete at 50°C during 240 days. Observation of these interfaces and of the microstructure, in general, demonstrate that the conditionings of mortar-wrapped bars in water do not affect the microstructural properties of the GFRP bars, even if the bars show pre-existing cracks or microcracks. The micrographs of external surfaces of unconditioned specimen, specimen aged in moist concrete at 50°C during 240 days and specimen pre-loaded at 80 percent of the UTS and aged in moist concrete at 50°C during 240 days are shown in Figure 10. The comparison of these micrographs shows that there was no significant damage occurring to mortar-wrapped GFRP bar surface, even at high temperature (50°C) and when bar presents pre-existing cracks and microcracks.



(a) (b)

Figure 9 Micrographs of fibre/matrix interface (X3000) of: a) unconditioned GFRP bar specimen, b) Conditioned GFRP bar specimen aged in moist concrete at 50°C for 240 days.

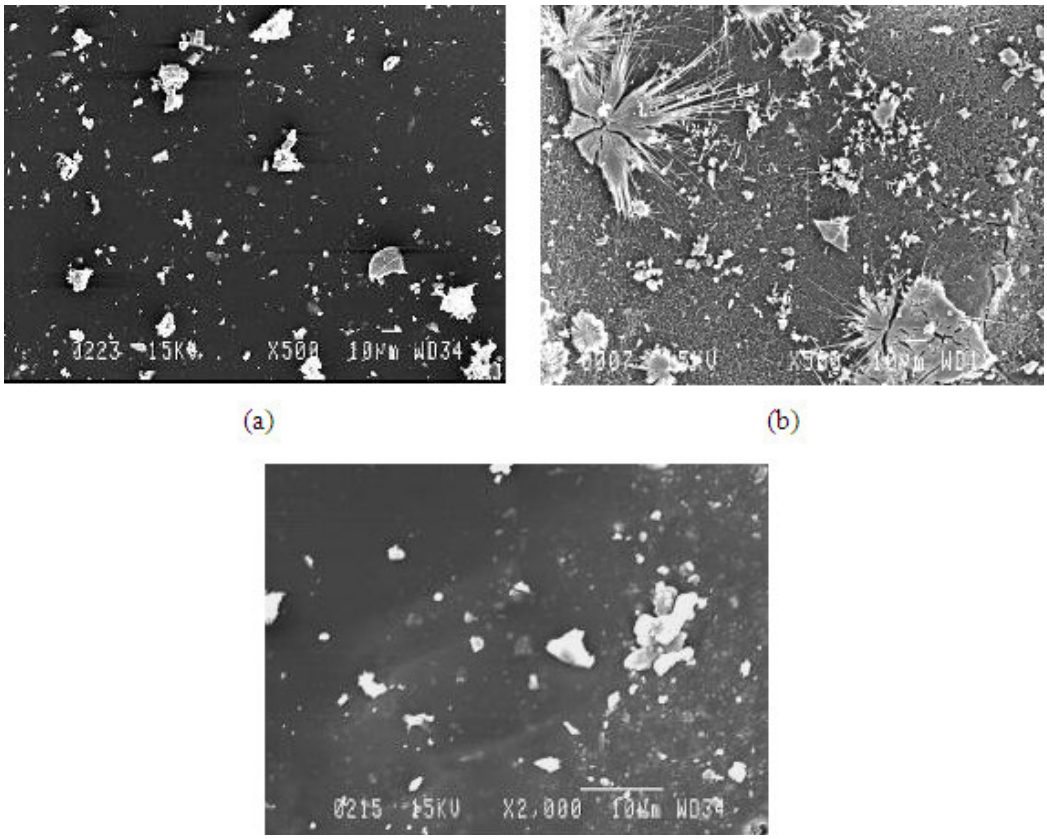


Figure 10 Micrographs of external surfaces for : a) reference, b) bar aged in moist concrete at 50°C during 240 days, c) bar pre-loaded at 80% of the UTS and aged in moist concrete at 50°C during 240 days.

3.1.7 Effect on Polymer Matrix

Table 4 presents the glass transition temperature (T_g) values found by DSC for unconditioned specimen, specimen aged in moist concrete at 50°C during 240 days and specimen pre-loaded at 80 percent of the UTS and aged in moist concrete at 50°C during 240 days. Note that for the unconditioned and aged samples, the T_g corresponding to the second heating run is higher than that of the first scan. This shift indicates that the samples were not fully cured and that a post-curing phenomenon occurred during the second heating run. However, it can be seen from the results presented in Table 4 that no significant changes of the T_g value occur after aging in water at 50°C for 240 days, even for pre-loaded bars. This result shows that no major effect on the thermal properties of the resin, which could occur after conditioning of mortar-wrapped FRP bars, was detected by DSC.

Table 4 Glass transition Temperature measured by DSC

Condition	Temperature (°C)	Time of immersion (days)	T_g 1st run(°C)	T_g 2nd run (°C)
Reference			105	134
Embedded in moist concrete	50	240	104	129

3.2 Effect of Extreme Temperatures

3.2.1 Effect of Extreme Temperatures on Mechanical Properties

Figure 11 shows the relation between the tensile, shear and flexural strength of GFRP bars and the test temperature respectively. Figure 12 presents the relationship between the flexural modulus of elasticity (Storage Modulus (SM)) and temperature in the range of -100° to 350°C. The SM (flexural modulus) was used to measure the effect of temperature on the stiffness of the FRP material. The drop of SM (flexural modulus) beginning around 120°C corresponded to the glass transition of the polymer and the lower plateau to the viscoelastic state.

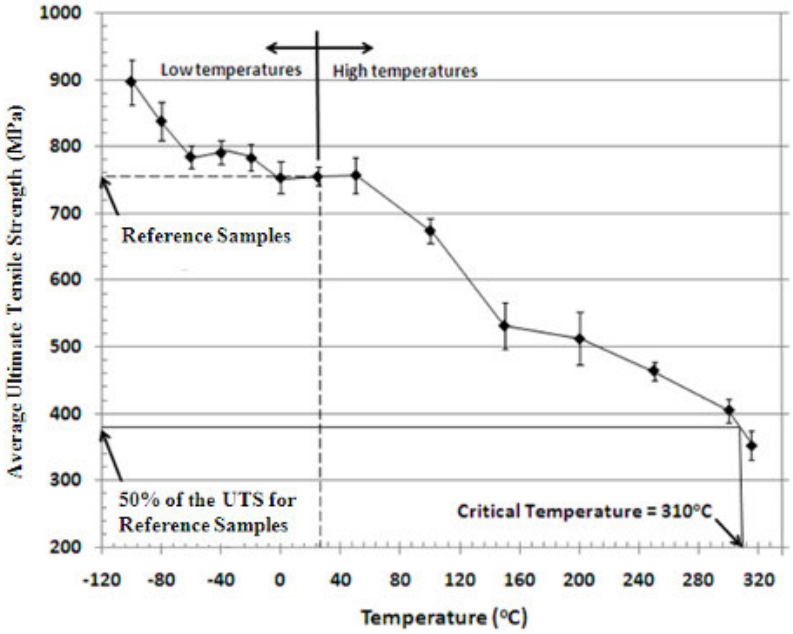


Figure 11 Tensile strength of GFRP bars tested at different temperatures

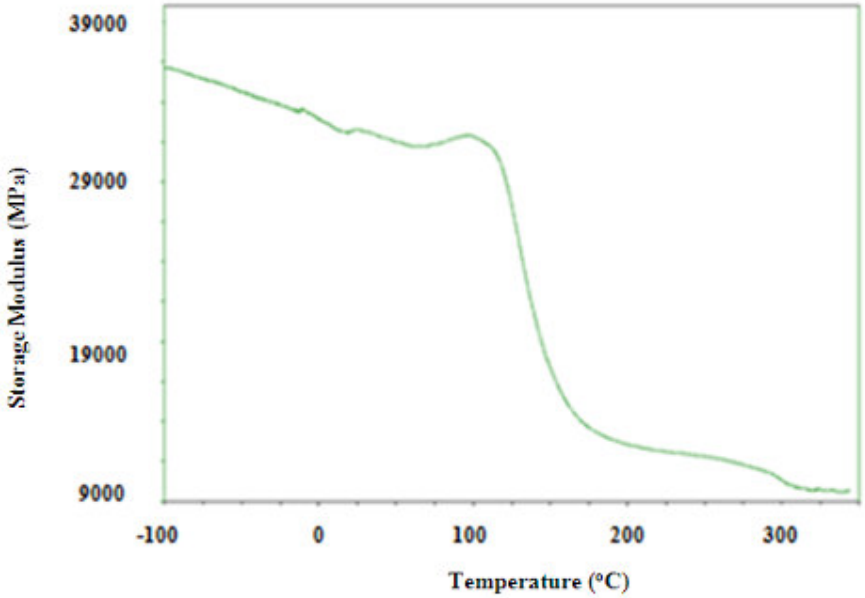


Figure 12 Flexural modulus of elasticity of GFRP bar specimen found by DMA between -100° and 350°C

Three different zones were identified in Figure 11: 1) the reference plateau between -40° and 50°C; 2) the zone where the stiffness increasing at temperatures lower than -50°C; and 3) the mechanical strength decreasing zone for temperatures near and above the glass transition temperature (T_g) of the polymer. The mechanical strengths between -40° and 50°C were stable. In this range of temperatures, the molecular chain mobility of the polymer did not change since the temperature was below T_g. This result showed that for standard environmental conditions of Nordic countries as Canada and north of USA (temperature ranging from -40 to 50 °C), the mechanical properties of GFRP bars were not changed. For temperatures lower than -50°C, the molecular chains mobility of the polymer decreased, leading to an increase of the mechanical stresses needed to rupture the material. Below T_g (around 120°C), the matrix was in a glassy state. When increasing the temperature and reaching the decomposition region, the breaking of molecular bonds started and the ductility of the material increased, leading to a decrease of mechanical strengths and stiffness of the material. At very high temperatures (greater than 300°C), strong degradation of the polymer occurred (combustion, oxidation…) and load transfer provided by the matrix was severely reduced.

If the critical temperature for FRP internal reinforcements is found from a tensile strength loss of 50 percents, such as for steel reinforcements, the results presented in Figure 11 can be used to determine the critical temperature for tested GFRP bars. Based on the experimental results, the critical temperature is equal to 310°C which is similar to the critical temperature found by Bisby and Kodur [28] for similar GFRP bars, and lower than the critical temperature of steel reinforcement, which is close to 500°C.

Figure 13 shows the failure mode for unconditionned and specimens exposed to temperature of 150°C during 2 hours. The tensile test of unconditioned specimens showed approximately a linear behavior up to the failure at any temperature. Specimens failing through the rupture of fibres, were accompanied by delamination of the fibres and matrix. A similar, but less dramatic failure was observed for specimens tested at high temperatures. It this case, it was noted that the delamination of fibres and matrix was more important than for unconditioned specimens. It was noted that the ultimate elongation slightly decreased at low temperatures but no significant change was noted at high temperatures. The increase of the tensile strength and flexural modulus and the decrease of ultimate elongation were constant in the temperature range. No ductile-brittle transition occurred in the GFRP materials at low temperature, contrary to steel which could present a ductile-brittle transition between -20° and -30°C [29].

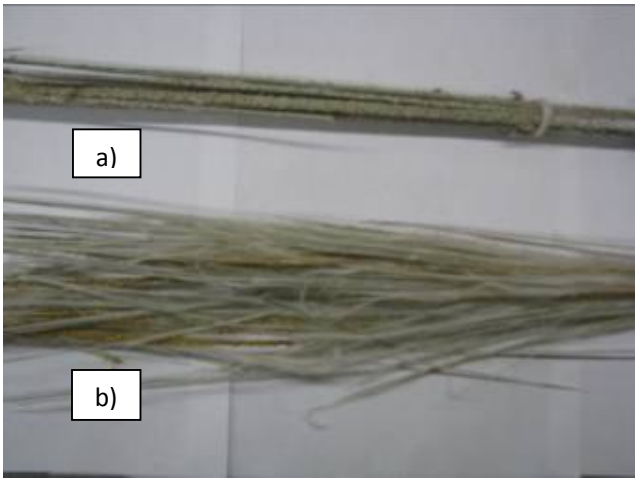


Figure 13 The failure mode of GFRP bars : a) tested at room temperature, and b) tested at 150°C.

3.2.2 Effect on Polymer Matrix

Figure 14 shows the mass variation of specimens as a function of temperature measured by TGA. It was seen that major weight loss occurred between 300 and 450°C. This important drop, up to 18%, was due to the thermal degradation of the polymer. At these temperatures, thermal degradation occurred and the molecular chains of the polymer broke, leading to the formation of microcracks both at the fibre/matrix interface and in the matrix phase (Figure 15). The weight losses measured by TGA showed a major degradation of the resin from 300°C to 450°C. Below this range of temperatures of degradation, the properties were recovered when the GFRP specimens were heated to the desired temperature and then tested at the ambient temperature. At this point, the experimental results suggest that irreversible loss of mechanical properties occurred above 300°C.

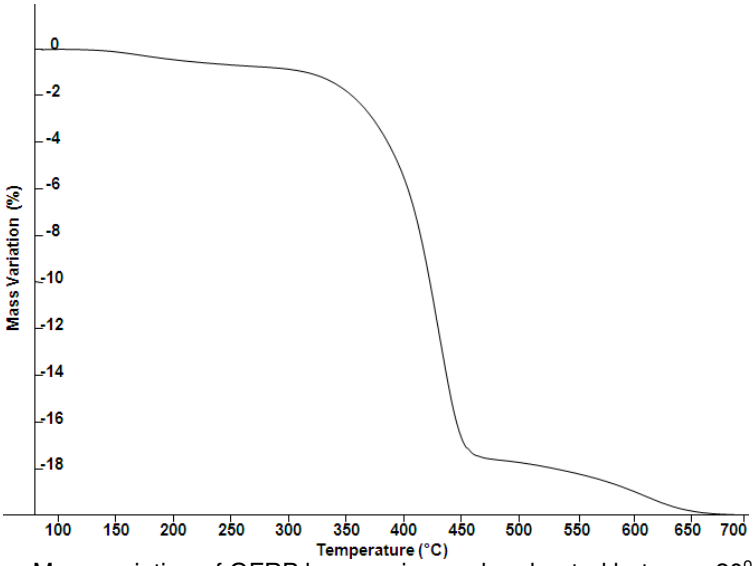


Figure 14 Mass variation of GFRP bar specimen when heated between 20° and 800°C.

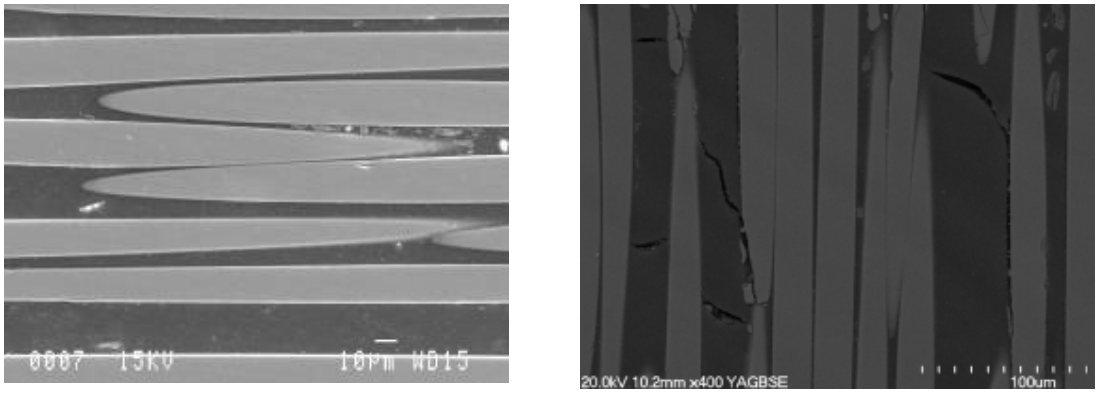
Table 5 shows T_g measured by DSC for reference and specimen heated at 350°C for 2 hours. Noted that, for reference samples, an exothermic peak corresponding to post-curing occurred after T_g. The T_g of the reference specimen was equal to 113°C, whereas the specimens heated at 350°C for 2 hours was equal to 67°C. This showed that the matrix weakened when heated at elevated temperatures, which explained the causes of the observed large decrease of mechanical properties.

Table 5 Glass transition Temperature measured by DSC

Condition	Temperature (°C)	Duration (hours)	T_g 1st run (°C)	T_g 2nd run (°C)
Reference	20	2	113	135
High Temperature	350	2	68.5	67

3.2.3 Microstructural Effect of Extreme Temperatures

The polymer matrix degradation was confirmed by microstructural analysis. The micrographs presented in Figure 15 show the polymer, the fibre and the interface between the fibres and matrix for reference specimen and specimen conditioned at 350°C for two hours. The comparison of these micrographs showed that significant damage occurred for GFRP bar conditioned at 350°C (Figure 15b) as compared to reference sample (Figure 15a). The presence of microcracks in specimen tested at 350°C confirmed the degradation of the polymeric matrix and explained the loss of mechanical properties.



(a) (b)

Figure 15 Micrographs of longitudinal fibre/ matrix interface of: a) unconditioned GFRP bar specimen, b) Conditioned GFRP bar specimen aged in air at 350°C for 2 hours.

4. Conclusions

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

1- The aging of mortar-wrapped GFRP bars in tap water is significantly less pronounced than traditional aging in simulated pore solution. The loss in the tensile strength and the microstructural/physical effects were significantly reduced.

2- Even at high temperature (50°C), where the environment is the more aggressive, the change in tensile strength is minor. For example, increasing the temperature of the solution from 40 to 50°C during 240 days results in a decrease of the tensile strength retention by 10 to 16% of the original tensile strength.

3- No significant microstructural changes were observed after 240 days immersion of GFRP bars embedded in concrete in tap water at 50°C. The interfaces between the bars and concrete and between the resin and the fibres don't seem to be affect by the moisture absorption and high temperatures.

4- The polymer matrix is not affected by moisture absorption and high temperatures: no changes of the glass transition temperature occur as observed by differential scanning calorimetry.

5- 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.

6- After 240 days water immersion of pre-loaded bar embedded in mortar, the retention rate of tensile strength are 95, 96 and 98% at 50, 40, and 23°C, respectively.

7- No significant microstructural changes were observed after 240 days immersion of GFRP bars embedded in mortar in tap water at 50°C after a pre-loading of 80% of the UTS. The interface between the resin and the fibres did not seem to be affected by the moisture absorption and high temperatures.

8- DSC analysis did not show any non-reversible degradation of the polymer chemical structure due to the aging of pre-loaded bars in moist concrete at 50°C during 240 days. No changes of the glass transition temperature occur as observed by differential scanning calorimetry.

9- Mechanical properties (tensile, shear and flexural strengths) and flexural elastic modulus of GFRP bars increased when the temperature decreased. This phenomenon was due to the increase of stiffness of the amorphous polymer matrix due to low temperatures.

10- At severe temperatures experienced in Northern regions such as Canada (temperature ranging from -40° to 50°C), the tensile strength and flexural modulus of elasticity appeared to be stable, which showed that the mechanical behavior of GFRP bars was not affected by temperature in this range of temperature

5. 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) and the Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada). The authors also want to thank the FRP bar manufacturer (Pultrall inc.) and The Ministry of Transportation of the province of Québec for their technical support.

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