Behavior of GFRP Reinforcing Bars Subjected to Extreme Temperatures

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Abstract: Corrosion of steel reinforced concrete members has stimulated the research on fiber-reinforced polymers (FRP) to be used as an internal reinforcement for concrete structures. The behavior of glass fiber-reinforced polymer (GFRP) reinforcing bars subjected to extreme temperatures is very critical for applications in North America, especially in Canada. There is a high demand for experimental studies to investigate the thermal stability of strength, along with the ultimate elongation, and modulus of GFRP bars. This paper evaluates the variation of mechanical properties of sand-coated GFRP reinforcing bars subjected to low temperatures (ranging from 0 to −100°C) and elevated temperatures (ranging from 23 to 315°C). Tensile, shear and flexural properties are investigated to get an overview of the thermal stability of mechanical properties of GFRP bars subjected to large variations of temperatures. Microstructural analyzes using scanning electronic microscopy (SEM), physical measurements by thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC), are also conducted to investigate the deterioration of fiber, matrix, and the fiber/matrix interface due to extreme temperatures. Increase of mechanical properties due to the matrix stiffness at lower temperatures, is also investigated. On the other hand, at very high temperatures, nearing about the glass-transition temperatures of the polymer matrix, the mechanical properties, especially the stiffness and the strength of the composites are decreased considerably.

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Introduction

Fiber reinforced polymer (FRP) composites, mainly based on thermoset polymers (vinylester) and glass or carbon fibers, are being used in infrastructures exposed to harsh environments involving deicing salts or marine environments. FRP reinforcing bar can be used instead of steel bar in the concrete structure because of its advantages due to the nature of the material used in its fabrication. In addition, it is used due to its high stiffness/weight ratio, high strength/weight ratio, corrosion resistance, and ease in fabrication. Under service conditions, concrete members reinforced with FRP bars are subjected to wide range of temperatures. Unfortunately, in some special conditions, such as very low temperatures and moist environment, the performance of the GFRP is still an unresolved question (Chu and Karbhari 2005; Karbhari et al. 2003).

Below zero temperatures can cause changes in mechanical properties and create additional microcracks in FRP materials. Microcracking at lower temperatures can further result in the increase of water absorption at higher temperatures, leading to an increased matrix plasticization and hydrolysis. The expansion of frozen water present in cracks and voids also results in debonding and transverse microcrack growth. Such freezing exposures lead to a material degradation through matrix cracking and fiber-matrix debonding, increased brittleness, and substantial changes in damage mechanisms those commonly observed under ambient conditions (Dutta 1992; Lord and Dutta 1988; Haramis 2003; Karbhari et al. 2000). Karbhari et al. (2002) investigated the effect of low-temperature thermal cycling on mechanical properties of carbon-vinyl ester composites and E-glass/vinyl ester composites. Their results indicated that freeze thaw could cause significant reduction of the mechanical properties and glass-transition temperatures of the FRP specimens immersed in an aqueous environment. The exposure to freeze-thaw cycles could also have larger effect on fiber-matrix bond deterioration and matrix cracking compared to any exposure.

On the other hand, the possibility of an exposure to fire to the concrete structures must also be considered during the design. Therefore, concerned building codes require specifying the basic properties to be considered regarding the fire resistance of all materials used in the structure. Reinforced concrete normally offers high fire resistance at low cost (Weber and Witt 2008). The use of combustible FRP reinforcement materials is, therefore, an issue which must be looked into seriously. The engineer during the design of a structure has to take into account the duration of time the structures can withstand high temperatures as well as fire exposures. It was well known that all FRP materials were susceptible to degradation of mechanical properties at high temperatures (Kodur et al. 2007). The polymer matrixes currently used for the fabrication of FRP reinforcing bars soften at temperatures approaching their glass-transition temperatures (T_g) resulting in re-

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Table 1. Mechanical and Physical Properties of 12.7 mm-Diameter GFRP Bar

	Property	Unity	Value	SD
Mechanical properties	Nominal tensile strength	MPa	788	25
	Nominal tensile modulus	GPa	47.2	2
	Tensile strain	%	1.70	0.1
	Nominal flexural strength	MPa	1095	40
	Nominal flexural modulus	GPa	52.6	3
	Flexural strain	%	2.15	0.16
	Nominal shear strength	MPa	185	10
Physical properties	Longitudinal coefficient of thermal expansion	$\times 10^{-6}/°C$	6.7	0.5
	Transverse coefficient of thermal expansion	$\times 10^{-6}/°C$	27.2	1.2
	Moisture absorption	%	0.62	0.02
	Glass content	% volume	64.3	3
		% weight	81.5	4

duction of mechanical properties, and potentially leading to the ineffectiveness of structural applications. This could be attributed to reductions in the mechanical properties of polymer matrix at high temperatures well above T_g leading to a reduced ability of the matrix to transfer forces between the fibers (Foster and Bisby 2008). Thus, for unidirectional FRPs such as those used predominantly in infrastructure applications, the matrix-dominated properties such as shear and bond strength are expected to be drastically reduced near T_g, which is typically between 100 and 120°C for vinylester matrix systems (Robert et al. 2009). It is well known that organic matrix based fiber-reinforced materials exhibit viscoelastic transitions followed by reversible and irreversible thermal degradation when exposed to elevated temperature, especially at temperature close or above the glass-transition temperature (T_g). The elastic modulus of a polymer will be significantly reduced above T_g, due to change in its molecular structure. The fibers, which exhibit better thermal properties than the matrix, can continue to support some load in the longitudinal direction until the temperature threshold of the fibers are reached. This occurs at temperatures near 980°C for glass fibers. However, the tensile properties of the composites are reduced due to reduction in force transfer between fibers through bond to matrix. Test results have indicated that 250°C (much higher than the glass-transition temperature) reduced the tensile strength of GFRP and CFRP composites by more than 20% (Kumahara et al. 1993). Other properties more directly affected by the shear transfer through the matrix, such as bending strength, which reduces significantly at higher temperature.

Based on available literature, Kodur and Baingo (1999) compared the behavior of FRP composites with those of traditional building materials at elevated temperature: the rate of strength loss was much greater to FRP than that of concrete and steel. FRP composites lost little strength when temperature was up to 100°C. After that temperature, they observed the strength degradation becoming much faster, resulting in 50% strength loss at 200°C, and in case of concrete, 50% strength loss not occurring up to about 700°C, whereas for steel, the corresponding temperature being 500°C. Further, Kodur and Baingo (1999) reported that the critical temperature for FRP composites was much lower than that of steel. In the same way Katz et al. (1999) determined that FRP reinforcing bars showed a reduction of between 80 and 90% in the bond strength as the temperature increased from 20 to 250°C compared to only 38% for steel reinforcing bars in the same temperature range. Effect of high temperature on the properties of FRP bars were studied by Kumahara et al. (1993), who found a reduction of 20% in the tensile strength of glass and carbon fiber FRP bars at a temperature of 250°C. Limited information is available related to the effect of very high temperatures. Sayed-Ahmed and Shrive (1999) noted that after 24 h at 200 and 300°C, the surface of Leadline had become darker, indicating some resin loss. Twenty-four hours of exposure at 400°C caused some of the fibers on the surface to become loose. Exposure to 500°C caused evaporation of the resin mainly within the first hour of exposure, reducing the tendon to a bundle of loose fibers. The reduction of tensile strength of aramid was 60% at 250°C. However, prolonged thermal aging at a high temperature combined with sustained loading could cause deterioration in the properties of the matrix (Uomoto 2004; Chin et al. 1998).

Therefore, the objective of this paper focuses on the investigation of the influences of severe temperatures on the degradation of GFRP bars used as internal reinforcement for concrete. The study is carried out using multiple performance data obtained from mechanical and physical characterization. In the present study, tensile, shear and flexural properties are investigated relating to the type of fiber and the quality of matrix. These mechanical tests are chosen to investigate the mechanical performance of GFRP bars submitted to different types of strains and stresses. The deterioration of bond properties for other types of FRP bars, exposed to extreme temperatures, will be reported in a further study.

Experimental Program

Material

Sand-coated glass FRP reinforcing bars manufactured by a Canadian company (Pultrall Inc., Thetford Mines, Quebec, Canada) are used for this study. The bars are made of continuous E-glass fibers embedded in vinylester matrix using a pultrusion process. The mass fraction of glass, as determined by thermogravimetric analysis according to ASTM E1131 (ASTM 2003a) standard, was equal to 81.5%. Their relative density according to ASTM D792 (ASTM 2000) standard was 1.99. The GFRP bars used have a nominal diameter of 12.7 mm; the mechanical and physical properties are summarized in Table 1.

Conditioning of GFRP Bar Samples

The GFRP bar samples were separated into two series: (1) unconditioned reference series; and (2) conditioned series, the samples of which are saturated in water. The moisture content at saturation

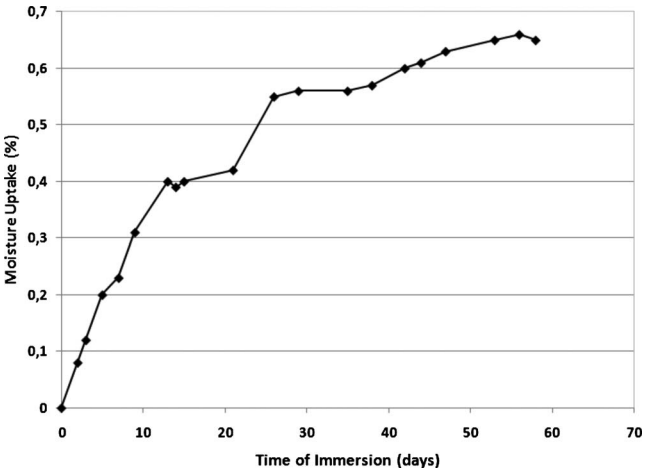


Fig. 1. Moisture absorption curve for 12.7-mm GFRP bar

of GFRP bars (0.65%) was reached by complete immersion of the specimens in water in accordance with procedure 7.4 of ASTM D570 standard except that a water temperature of 50°C was used. Fig. 1 shows the moisture absorption curve for 12.7 mm GFRP bars. All GFRP bar specimens were tested under extreme temperature conditions using a MTS environmental chamber cooled by liquid nitrogen (Fig. 2). Subzero temperatures equal to −100°, −80°, −60°, −40°, −20°, and also 0°C were chosen to simulate the effect of Nordic climate on GFRP bars. The temperatures below −60°C were used to amplify the effects of temperature on mechanical and microstructural behavior of the FRP materials. Elevated temperatures equal to 50°, 100°, 150°, 200°, 250°, and 325°C were chosen to simulate short-term environmental conditions in the case of fire. Kodur and Bisby (2005) presented a numerical model for evaluating the fire resistance of FRP-reinforced concrete slabs, based on a thermal analysis. The writers concluded that the predicted time to reach 350°C in a GFRP-reinforced concrete slab reinforced with GFRP was approximately 30, 60, and 185 min for concrete depths of 15, 30 and

Fig. 2. Tensile test specimen in environmental chamber

75 mm, respectively. 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.

Tensile Test Procedure

The effect of temperature on tensile strength of GFRP bars was measured on samples subjected to temperatures varying between −100° (cold temperature) to 325°C (elevated temperature). GFRP bars samples were cut to a length of 1440 mm and were tested under tension according to ASTM D7205. The test was carried out using MTS 810 testing machine equipped with 500 kN load cell and the load was increased until failure. For each tensile test, the specimen was mounted on the press with steel pipe anchors gripped by the wedges of upper and lower jaws of the machine. The rate of loading ranges between 250 and 500 MPa/min. The applied load was recorded during the test using a data acquisition system monitored by a computer. The bar elongation and tensile modulus of elasticity were not recorded during the test due to severe temperatures of conditioning which could have damaged the elongation measurement device.

Shear Test Procedure

The transverse shear strengths of GFRP bar samples were measured on samples subjected to temperature varying between −100° (cold temperature) to 325°C (elevated temperature). The transverse shear test was conducted according to ACI 440.3R-04 [American Concrete Institute (ACI) 2004]. This property was investigated to provide some indications on the retention of the matrix related mechanical properties of GFRP bars subjected to high and low temperatures. All specimens were cut at a length of 200 mm and tested in shear according to ACI 440.3R-04. The tests are carried out using MTS 810 testing machine equipped with 500 kN load cell. The distance between the shear planes was set to 50 mm. The rate of loading was chosen to allow an increase of 30 to 60 MPa/min of the shearing stress and the load is applied without subjecting the test specimen to any shock. The applied load was recorded during the test using a data acquisition system monitored by a computer.

Flexural Test Procedure

The flexural properties of GFRP bar samples were measured on samples subjected to temperature varying between −100° (cold temperature) to 325°C (elevated temperature). Flexural tests were conducted according ASTM D4476 (ASTM 2003b) standard. This method was used with some modifications, such as using full bars instead of half bar (cut longitudinally). All specimens were cut at a length of 300 mm and an overhang of 10% of the supported span was allowed at each support. The tests were carried out using MTS 810 testing machine equipped with 500 kN load cell. The specimens were loaded under load control at a rate corresponding to a stress of 5 MPa/sec approximately.

Dynamical Mechanical Analysis

Dynamical mechanical analysis (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. DMA was used to measure the elastic modulus instead the former test since it was not possible to use the LVDT at high and low temperatures to determine the flexural modulus of elasticity. The tests were carried out according to ASTM D5023 (ASTM 2007) 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 frequency was set to 1Hz and the heating rate to 5°C/min. The rate of loading is chosen to allow a deflection of 10 microns.

Thermogravimetric Analysis

Thermogravimetric analysis (TGA) determined the changes in weight of FRP composites as a function of temperature. The TGA could be used to calculate glass fiber 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 E1868 (ASTM 2004) 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}.

Differential Scanning Calorimetry

Differential scanning calorimetry (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, twelve to fifteen milligram specimens were cut from reference GFRP samples (nonconditioned and specimens conditioned) were placed in aluminum pans for two hours at 350°C and 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 E1356 (ASTM 2008) standard. If a decrease of T_g was observed for conditioned samples, it was an indication of plasticizing effect or chemical degradation. These phenomena of degradation could confirm the presence of irreversible degradation phenomena at high temperature observed by TGA. Aged sample maintaining a lower T_g than for the reference showed an irreversible chemical degradation.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) observations and image analysis were performed to evaluate the microstructure of specimens and the integrity of the FRP material after exposure to severe temperatures. The samples observed in SEM are (1) reference specimens; (2) specimens exposed to temperatures ranging from −100° to 325°C; and (3) saturated specimens exposed to ambient temperature and to the temperature of −100°C. All specimens observed in the SEM were first cut, polished, and coated with a thin layer of gold-palladium by a vapor-deposit process. Microstructural observations were thereafter performed on a JEOL JSM-840A SEM. These observations were conducted to determine the potential degradation of the polymer matrix, glass fibers, or interface, if any. SEM observations could also explain the changes of mechanical properties and the irreversible mechanisms of degradation observed by TGA or DSC.

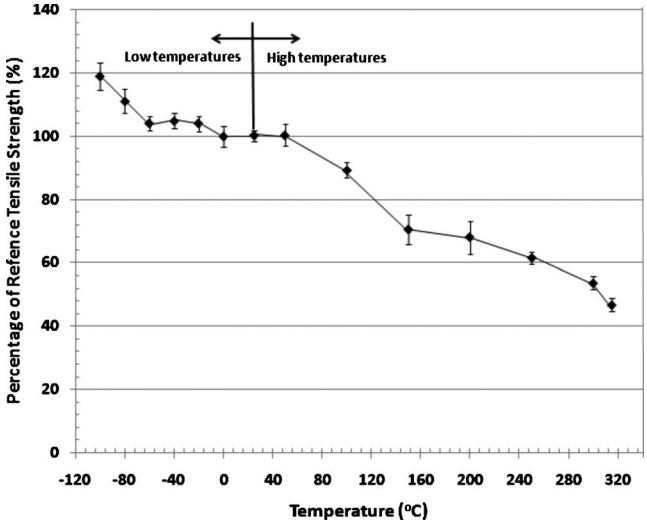


Fig. 3. Normalized average tensile strength with standard deviation of GFRP bar specimens tested under different temperatures

Tests Results and Discussion

Effect of Temperature on Mechanical Properties

Figs. 3–5 show the relation between the tensile, shear and flexural strength of GFRP bars and the test temperature respectively. Table 2 shows the detailed experimental results for tensile, shear and flexural tests. Fig. 6 presents the relationship between the flexural

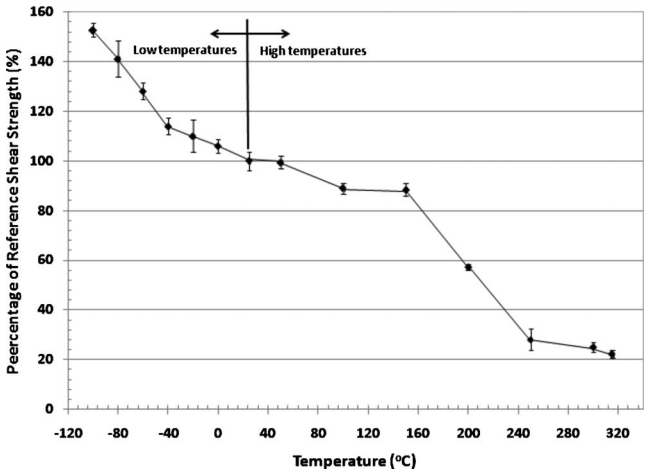


Fig. 4. Normalized average shear strength with standard deviation of GFRP bar specimens tested under different temperatures

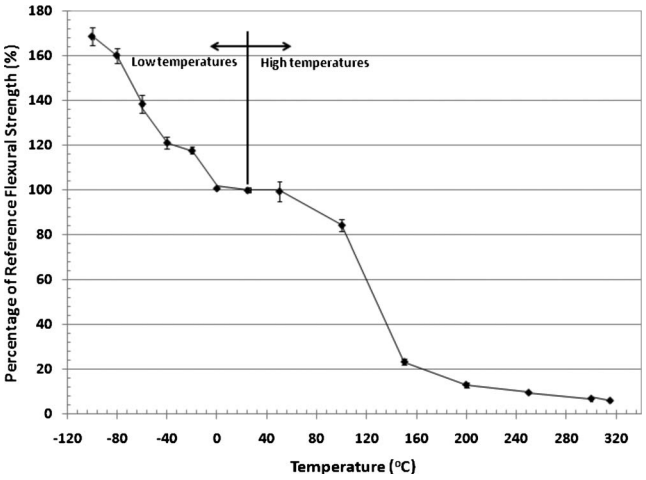


Fig. 5. Average flexural strength with standard deviation of GFRP bar specimens tested under different temperatures

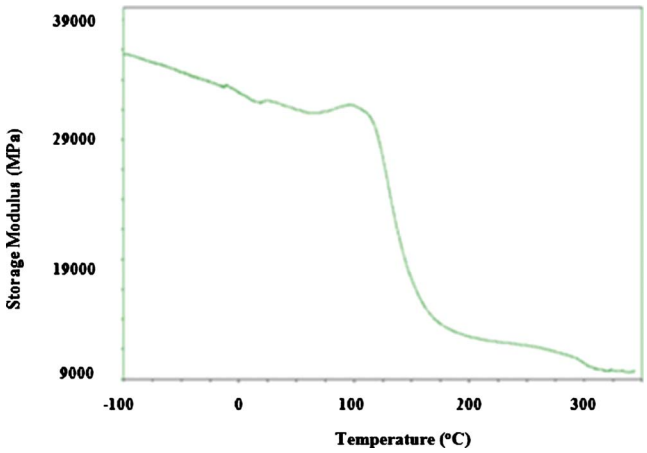


Fig. 6. Flexural modulus of elasticity of GFRP bar specimen found by DMA between −100° and 350°C

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.

Three different zones were identified in Figs. 3–6: (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 U.S.A. (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. The results presented in Table 2 are in accordance with tensile strength losses recorded by Wang et al. (2007). According to the writers (2007), similar bars lost 50% of their tensile strength when tested at 300°C, compared to a 46% drop for the present study. Sayed-Ahmed and Shrive (1999) concluded that CFRP bars lost approximately 40% of their tensile strength when tested at 350°C. It can also be observed in Figs. 3–5 that the shear and flexural strengths were much more sensitive to high temperature than tensile strength. Only the polymer matrix could be affected by high temperature (above 300°C) used in this study. The tensile properties were more related to fibers' strength, since the load was applied in the fibers direction, the tensile strength was less affected by the polymer degradation rather than the shear and flexural strengths. On the other hand, shear and flexural strengths were related to the interface between fibers and resin which was directly affected by the degradation of polymer resin.

Table 2. Experimental Results of Mechanical Tests

Temperature (°C)	Number of test samples	Tensile strength (MPa)	COV (%)	Shear strength (MPa)	COV (%)	Flexural strength (MPa)	COV (%)
−100	5	897	3.7	304	1.8	1843	2.4
−80	5	838	3.5	281	5.1	1750	2.2
−60	5	785	2.0	255	2.6	1516	2.9
−40	5	791	2.2	227	3.0	1325	2.3
−20	5	784	2.4	219	5.9	1288	1.4
0	5	754	3.2	211	2.6	1101	0.3
25	5	756	1.8	199	3.8	1093	2.1
50	5	757	3.5	198	2.5	1088	4.5
100	5	674	2.7	177	2.6	922	3.1
150	5	532	6.6	176	2.8	255	5.1
200	5	513	7.4	114	2.1	142	8.1
250	5	464	2.9	56	14.8	106	5.7
300	5	405	2.8	50	7.6	74	6.8
325	5	353	3.2	44	7.0	65	4.2

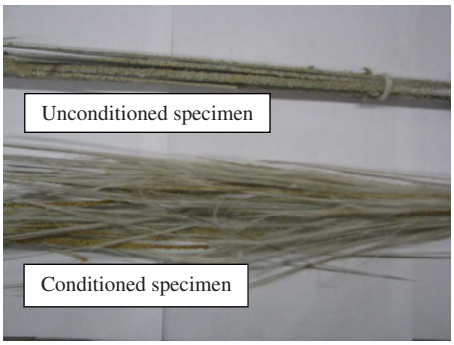


Fig. 7. Failure mode of unconditioned and conditioned specimens after tensile tests

Fig. 7 shows the failure mode for unconditioned and conditioned specimens after tensile tests. The tensile test of unconditioned specimens showed approximately a linear behavior up to the failure at any temperature. Specimens failing through the rupture of fibers were accompanied by delamination of the fibers 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 fibers 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 (Panigrahi 2006).

Effect of Moisture Absorption on Shear and Flexural Properties of GFRP Samples Subjected to Low Temperature

Figs. 8 and 9 show the relationship between the shear and the flexural strengths and the test temperature for reference and saturated GFRP bars, respectively. At ambient temperature, where the water was liquid, there was no effect on the strengths. When temperature became lower than 0°C, the shear and flexural strengths of the GFRP bars increased for both types of (samples, reference and saturated). However, the increasing rate was smaller for the saturated sample. At these temperatures, the absorbed water froze and its volume expands. This volume expansion led to an internal stress and could cause the initiation of microcracks in the polymer matrix (Fig. 12). These microcracks explained the causes of smaller increasing rate of shear and flexural strengths for saturated samples. It could also be observed from Figs. 8 and 9 that the difference between the strengths of the reference and the saturated samples was nearly same, around 10%, between 0° and −100°C. This observation was explained by the fact that the expansion of absorbed water occurred only one time at the freezing temperature (0°C).

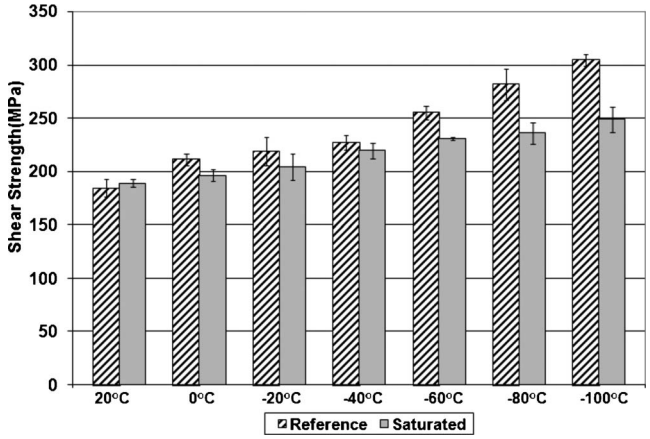


Fig. 8. Average shear strength with standard deviation of unconditioned and saturated GFRP bars tested at low temperature

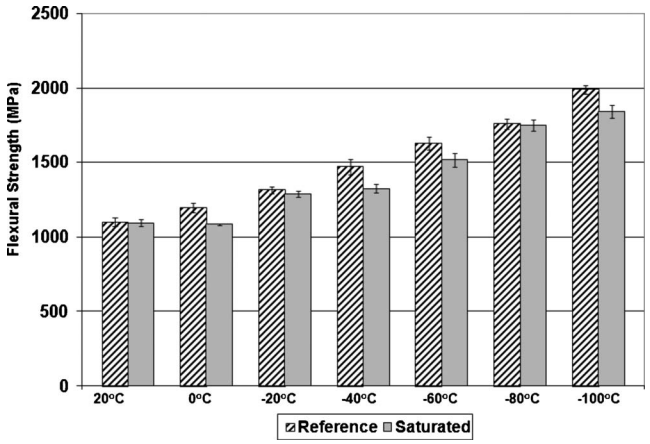


Fig. 9. Average flexural strength and standard deviation of unconditioned and saturated GFRP bars tested at low temperature

Effects on Polymer Matrix

Fig. 10 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 fiber/matrix interface and in the matrix phase

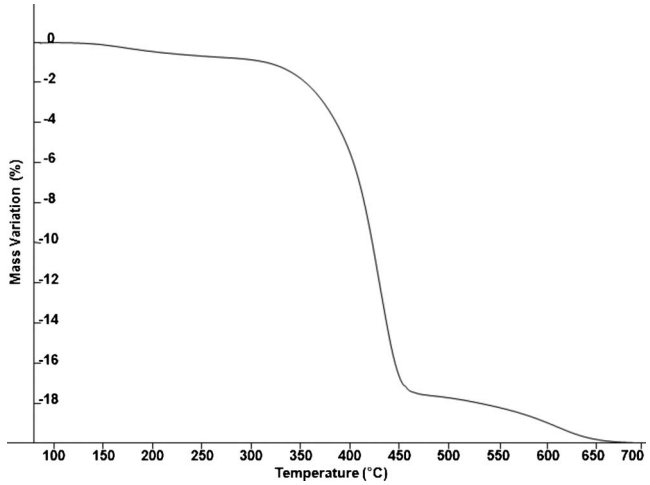


Fig. 10. Mass variation of GFRP bar specimen when heated between 20° and 800°C

Table 3. Results of Differential Scanning Calorimetry (DSC) Analysis

Conditioning	Temperature (°C)	Duration (h)	T_g run 1 (°C)	T_g run 2 (°C)
Unconditioned			112	113
Exposed to high temperature	350	240	67	68

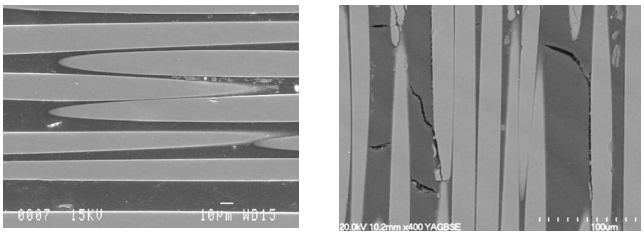
(Fig. 12). The weight losses measured by TGA showed a major degradation of the resin from 300°C to 450°C. Below this range of temperatures of degradation, the properties were recovered when the GFRP specimens were heated to the desired temperature and then tested at the ambient temperature. At this point, the experimental results suggest that irreversible loss of mechanical properties occurred above 300°C.

Table 3 shows T_g measured by DSC for reference and specimen heated at 350°C for 2 h. Noted that, for reference samples, an exothermic peak corresponding to postcuring 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 h 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.

Microstructural Effects

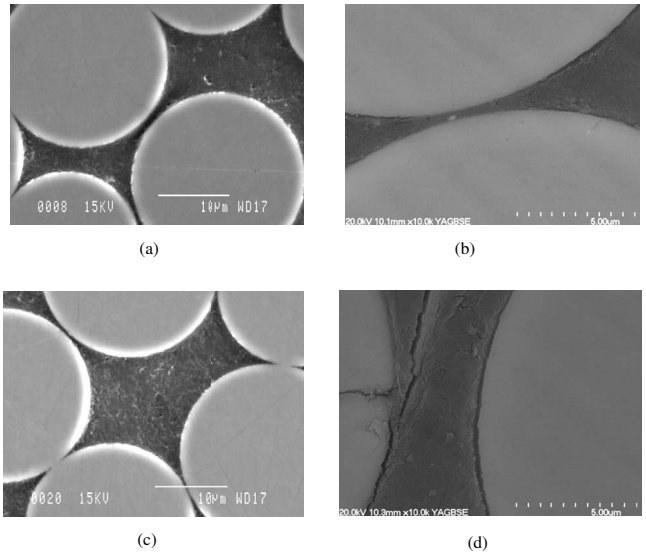
The polymer matrix degradation was confirmed by microstructural analysis. The micrographs presented in Fig. 11 show the polymer, the fiber and the interface between the fibers and matrix for reference specimen and specimen conditioned at 350°C for two hours. The comparison of these micrographs showed that significant damage occurred for GFRP bar conditioned at 350°C [Fig. 11(b)] as compared to reference sample [Fig. 11(a)]. The presence of microcracks in specimen tested at 350°C confirmed the degradation of the polymeric matrix and explained the loss of mechanical properties.

Fig. 12 shows the effect of moisture absorption at low temperature on GFRP microstructure. The micrographs presented in Fig. 12 show the polymer matrix, the glass fibers and the interface between the fibers and matrix for an unconditioned reference specimen [Fig. 12(a)], a dry specimen conditioned at −100°C [Fig. 12(b)], a specimen saturated in water without any subsequent conditioning [Fig. 12(c)] and a specimen saturated with water and conditioned at −100°C for two hours [Fig. 12(d)]. The comparison of micrographs b and d in Fig. 12 indicated that a significant damage occurred in the saturated GFRP bar conditioned at −100°C compared to the dry specimen conditioned in the same conditions. The comparison of micrographs a and c



(a) (b)

Fig. 11. Micrographs of longitudinal fiber/matrix interface



(a) (b) (c) (d)

Fig. 12. Micrographs of transversal fiber/matrix interface

showed that the microstructural damages were not induced by the moisture absorption, but by the combination of water absorption and conditioning at very low temperatures.

The presence of microcracks in the saturated specimen tested at −100°C confirmed the degradation of the polymeric matrix caused by the volume expansion of the water at low temperature and could explain the difference between the shear and flexural strengths of the reference and the saturated samples tested at low temperatures. The observation of micrograph 12b confirmed that no damage occurred in the specimen conditioned in air at −100°C. Since no damage was observed on sample conditioned in air at −100°C, it was expected that no damage would occur at standard temperature of application (−40°C).

Summary and Conclusions

Based on these results, the following conclusions were drawn:

1. 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. Furthermore, if the material contained a high level of moisture, the volume expansion of the water during the freezing could cause the initiation of microcracks and decrease the mechanical properties, (which compete) with the increase of stiffness of the matrix. However, it was observed that the shear and flexural strengths of the saturated GFRP samples subjected to low temperatures (between 0° and −60°C) were not affected.
2. 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.
3. At high temperatures, near and above T_g (T_g is around 120°C), the mechanical strength and flexural modulus dropped because of the change of state in the polymer and the reaction of degradation. At very high temperature (350°C), microcracks in polymer due to a thermal degrada-

tion of the polymer matrix were observed and they led to a decrease of the tensile strength and flexural modulus.

4. Important degradation phenomena occurred in polymer matrix at temperatures around 350°C. The measured weight loss recorded was 18% and the T_g fall from 113°C to 67°C after conditioning the GFRP samples at 350°C for 2 h.

Finally, it must be kept in mind that the conditionings used in the present study were harsher than the real situations because the tested GFRP bar samples were directly in contact with air, which was not the case in field situation (bars embedded in concrete). In fact, the reaction of decomposition of bars embedded in concrete would be slower because of absence of oxidation reaction of the polymer matrix.

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