

Effects of Diameter on the Durability of Glass-Fiber-Reinforced-Polymer (GFRP) Bars Conditioned in Alkaline Solution

Brahim Benmokrane,¹ Allan Manalo,² Jean-Charles Bouhet,³ Khaled, Mohamed⁴,
and Mathieu Robert⁵

ABSTRACT

Current standards do not consider the diameter of glass-fiber-reinforced-polymer (GFRP) bars used as internal reinforcement in concrete structures to be a factor influencing bar durability. This paper investigates the effects of bar diameter on the physical and mechanical properties as well as the durability of GFRP reinforcing bars conditioned for three months at 60°C in an alkaline solution simulating a concrete environment. Five diameters (nominal diameters of 9.5 mm, 12.7 mm, 15.9 mm, 19.1 mm, and 25.4 mm) were considered; bar properties were assessed before and after conditioning. Microstructural analyses and measurement of physicochemical properties were also carried out. The results show that bar size had no significant effect on bar physical properties, except for water absorption. The smaller diameter bars had higher water absorption than the larger ones due to their higher surface-area-to-volume ratios. In the case of the unconditioned bars, the tensile strength and modulus were not significantly affected by bar diameter, but there was a size effect for interlaminar shear strength and flexural strength. On the other hand, the conditioning in the alkaline solution had a greater negative effect on the tensile strength of the larger bars than on the smaller ones. Scanning-electron-microscope (SEM) observations and Fourier-transform-infrared-spectroscopy (FTIR) analysis revealed that the degradation remained at the surface of all the conditioned specimens. Nevertheless, there were only small variations between the physical and mechanical properties of the GFRB bars of

25 different diameters. This indicates that the current provisions in standards that do not relate
26 strength-retention limit to bar size are acceptable.

27

28 **Keywords:** GFRP reinforcing bars; diameter; durability; mechanical; properties retention; alkaline
29 environment, concrete

30

31

32 ¹Professor, Canada Research Chair in Advanced Composite Materials for Civil Structures,
33 NSERC Research Chair in Innovative FRP Reinforcement for Concrete Infrastructures,
34 Department of Civil Engineering, University of Sherbrooke, Sherbrooke, Quebec, Canada, J1K
35 2R1, Phone: 819-821-7758, Fax: 819-821-7974, E-mail: Brahim.Benmokrane@USherbrooke.ca

36 ²Senior Lecturer, Centre for Future Materials, Faculty of Health, Engineering and Sciences,
37 University of Southern Queensland, Toowoomba, Queensland 4350, Australia. E-mail:

38 Manalo@usq.edu.au

39 ³M.Sc Candidate, Department of Civil Engineering, University of Sherbrooke, Sherbrooke,
40 Quebec, Canada J1K 2R1, E-mail: jc.bouhet@hotmail.fr

41 ⁴Postdoctoral Fellow, Department of Civil Engineering, University of Sherbrooke, Sherbrooke,
42 Quebec, Canada J1K 2R1, E-mail: Khaled.Mohamed@usherbrooke.ca

43 ⁵Professor, Dept. of Civil Engineering, Univ. of Sherbrooke, QC, Canada J1K 2R1. E-mail:
44 Mathieu.Robert2@usherbrooke.ca

45

46 **INTRODUCTION**

47 Glass fiber-reinforced-polymer (GFRP) bars have emerged as an attractive alternative to steel
48 reinforcement in concrete structures because of their corrosion performance in aggressive
49 environmental conditions. These composite reinforcing bars have attracted significant interest
50 because of their superior properties such as light weight, high mechanical properties, and
51 neutrality with respect to electrical and magnetic disturbances. The results of several
52 experimental studies, establishment of materials specifications, publication of design codes and
53 guidelines, and successful field applications in concrete structures have driven the worldwide use
54 and acceptance of GFRP bars (ACI 440.1R, CSA S6, CSA S806, CSA S807, fib 2007,
55 Benmokrane et al. 2006; Drouin et al. 2011, Manalo et al. 2014; Mohamed and Benmokrane,
56 2016 & 2015, Arafa et al, 2016, Ahmed et al., 2016). As a result, a variety of GFRP bars
57 manufactured with various fibers and resins as well as various surface geometries are now
58 commercially available (ACI 440.1R). Like steel reinforcement, GFRP bars are available in
59 diameters ranging from 6 mm to 36 mm (ACI 440.1R); larger diameter bars can be also
60 manufactured. Unlike steel reinforcement, whose properties can be assumed to be the same for
61 different bar diameters, GFRP bars are size dependent in terms of longitudinal strength due to
62 shear-lag effect (Bank 2006). To illustrate, Hollaway (2008) measured a reduction in tensile
63 strength of up to 40% when the bar diameter increased from 9.5 mm to 20 mm. For these
64 reasons, manufacturers are required to fully report the characteristic strength, stiffness, physical,
65 and durability properties for every type and size of FRP bar.

66 The mechanical, physical, and durability characteristics are important information needed in
67 the material specifications and design of FRP bars. These properties should be determined in
68 accordance with the prescribed test standards and methods (ACI 440.6, CSA S807). They must

69 also be made available to design engineers, asset owners, and building-code and standard-writing
70 authorities (Micelli and Nanni 2004). More importantly, the physical, mechanical, and durability
71 properties of every commercially available and newly developed GFRP bar should comply with
72 the limits specified in the current standards and specifications (ACI 440.6, CSA S807). While the
73 minimum specified mechanical properties are available for each bar diameter, the current ACI
74 and CSA standards and specifications (ACI 440.6, CSA S807) do not relate the requirement
75 limits in terms of physical and durability properties to FRP-bar size. This is because there have
76 been few studies investigating the effect of GFRP-bar size on physical and durability properties.

77 The durability of GFRP bars is a complex problem because it depends upon the components
78 of the composite material (Bakis, 1993, Benmokrane and Rahman 1998, Hollaway 2010). In
79 particular, the reaction of GFRP bars to the alkali in concrete has received significant attention
80 due to their importance in construction applications (Porter et al. 1997, Bakis et al. 1998,
81 Nkurunziza et al. 2005, Chen et al. 2007, Robert et al. 2013, Belarbi and Wang 2012, Kamal and
82 Boulfiza 2011). As internal reinforcement, FRP bars are embedded in a cementitious
83 environment aggressive to glass FRPs (GFRPs) due to the high pH level of the pore-water
84 solutions and the presence of alkali ions (Porter et al. 1997, Micelli and Nanni 2004, Robert et al.
85 2009). Most of the cases available to date focusing on the physical and durability properties of
86 GFRP bars have involved small-diameter bars. Tannous and Saadatmanesh (1999) investigated
87 the durability characteristics of 10 mm and 19.5 mm diameter vinyl ester and polyester-based
88 AR-Glass FRP bars. Their results showed very small changes in the elastic modulus (0% to 2%).
89 The tensile strength retained after 6 months exposure to an alkaline solution (pH=12) at 60 °C
90 was only 72% to 77% for 10 mm bars, but 83% to 86% for 19.5 mm diameter bars. Furthermore,
91 they indicated that vinyl ester provided better protection to fibers against chemical attack than

92 polyester. Similarly, Micelli and Nanni (2004) investigated the durability of GFRP rods
93 subjected to alkaline exposure and high temperature (60 °C). While they considered two different
94 diameters of GFRP rods, the 12 mm diameter bars were made from thermoplastic resin, while
95 the 6.35 mm diameter bars were made from polyester resin. Their results revealed no degradation
96 in the GFRP bars made with thermoplastic resin, but a reduction in tensile strength of up to 40%
97 in the bars made with polyester resin after 42 days. Robert et al. (2009) conducted an accelerated
98 aging test of 12.7 mm vinylester based GFRP bars with a fiber content of 77.9% by weight
99 embedded in concrete. They found that the GFRP bars in alkaline solution experienced strength
100 losses more than 3 times that of the GFRP bars aged in moist concrete. Most recently,
101 Benmokrane et al. (2015) conducted a comparative durability study of 6 mm glass/vinylester,
102 basalt/vinylester, and basalt/epoxy FRP bars. Their test results revealed that basalt/epoxy FRP
103 bars has better mechanical property retention than basalt/vinylester. The results from these
104 studies primarily provide the basis which the current design guidelines and codes can use in
105 developing generalized requirement limits as well as similar environmental reduction factors for
106 all GFRP-bar sizes. Clearly, there is a gap in research investigating the durability characteristics
107 of GFRP bars of different sizes and correlating them with their important physical and
108 mechanical properties.

109 This paper systematically investigates the physical and mechanical properties of GFRP bars
110 of different diameters. It aims to correlate the physical and long-term characteristics of FRP bars
111 with bar diameters for their effective use and to provide guidance in the development of design
112 codes and material specifications for this reinforcing material. In the first stage, the physical and
113 chemical properties of the unconditioned bar materials were determined. In the second stage, the
114 GFRP bars were exposed to alkaline solution for 3 months at 60°C to simulate the concrete pore

115 environment. Mechanical characterization of these conditioned bars was then conducted and
116 compared to that of the unconditioned bars. Microstructural analyses and measurements of the
117 physicochemical properties were also carried out on the conditioned and unconditioned GFRP
118 bars. The findings from these studies are provided in this paper.

119 **EXPERIMENTAL PROGRAM**

120 **Materials**

121 The sand-coated GFRP bars used in this study were made of continuous boron-free glass fibers
122 (EC-R) impregnated in a vinylester-based resin matrix and were manufactured according to the
123 pultrusion process by a Canadian company (Pultrall Inc., Thetford Mines, Quebec). Five
124 diameters of GFRP bars were investigated (#3, #4, #5, #6, and # 8), which correspond to nominal
125 diameters of 9.5 mm, 12.7 mm, 15.9 mm, 19.1 mm, and 25.4 mm, respectively, as shown in
126 Figure 1. The technical specifications for these bars can be found in the data sheets reported by
127 Pultrall (2012).

128 **Specimen Details**

129 The preparation of specimens and characterization of the physical and mechanical properties of
130 the GFRP bars were performed according to the appropriate ASTM, ACI, and CSA test
131 standards. Table 1 summarizes the test methods as well as the number of specimens tested for
132 each type of test and bar size. The specimens were cut and prepared in accordance with the
133 recommendation of the appropriate test standards.

134 **Bar Conditioning**

135 The GFRP bars were separated into two series. The first series consisted of unconditioned
136 reference bars; the second comprised GFRP bars conditioned in an alkaline solution for 90 days
137 at 60°C. The alkaline solution used comprised 118.5 g of Ca(OH)₂, 0.9 g of NaOH, and 4.2 g of

138 KOH for 1 L of water. The solution had a pH of 12.6, which is representative of a mature
139 concrete pore solution. The conditioning temperature was set at 60°C, as specified in ASTM
140 D7705/D7705M-12 (2012). The conditioning was conducted in accordance with ACI 440.3R-12
141 (2012), Test method B.6, and CSA-S806-12 (2012), Annex O. During conditioning, the level of
142 alkaline solution and pH level were checked periodically, and new solution added as necessary.

143 **PHYSICAL PROPERTIES OF THE GFRP BARS**

144 Table 2 summarizes the physical properties of the GFRP bars. The values listed within
145 parentheses represent the standard variation of the test results.

146 **Actual Cross-Sectional Area by Immersion Test**

147 The actual cross-sectional area of the GFRP bars was measured in accordance with CSA-S806
148 (2012), Annex A. A plastic cylinder and a scale capable of measuring weight up to an accuracy
149 of 1 g were used. Twenty-four 270 mm long specimens were prepared for each bar diameter and
150 tested. All specimens were kept in the test environment for 24 hours prior to weighing and
151 measuring. All the bars are oversized when compared to their respective nominal cross-sectional
152 areas (Table 2). The average measured oversize varied from 9% to 18%, as seen with the largest
153 (#8) and smallest (#3) bars, respectively. This variation is due to the ratio difference of the sand
154 coating to the core. According to the average measured surface area, all bar diameters meet the
155 Grade III requirements of the Ministry of Transport Ontario's special provision for glass-fiber-
156 reinforced-polymer reinforcing bar.

157 **Fiber Content**

158 The fiber content of the GFRP bars was calculated according to ASTM D3171-15 (2015). Nine
159 specimens for each bar diameter were identified, dried, and weighted. The bars were then placed
160 in an oven at 650°C until the polymer matrix was entirely removed by combustion. The

161 remaining fibers were weighed in order to get the fiber weight ratio. Since the bars were sand
162 coated, the weight of the sand was measured separately and subtracted from the initial weight.
163 Table 2 shows that the fiber content increased slightly with bar diameter, from 80.9% of fibers
164 by weight for the #3 bars to 83.0% for the #8 bars. It should be noted, however, that the limits
165 specified in CSA S807 (2010) for the glass fiber fraction by weight is only 70%.

166 **Transverse Coefficient of Thermal Expansion**

167 The transverse coefficient of thermal expansion was calculated according to ASTM E1131-08
168 (2014). Nine specimens were tested for each bar diameter. The measurements were conducted
169 between -30°C and 60°C at a heating rate of 3°C. A TA Q400 thermomechanical analyser was
170 used. Cryogenic equipment (liquid nitrogen) was used to reach subzero temperatures. The results
171 show that the coefficients of thermal expansion for the different bar diameters fall between
172 $20.5 \times 10^{-6}/^{\circ}\text{C}$ and $22.0 \times 10^{-6}/^{\circ}\text{C}$, which is only half of the limit of $40.0 \times 10^{-6}/^{\circ}\text{C}$ specified in CSA
173 807 (2010).

174 **Void Content**

175 The void content of the GFRP bars was measured with the wicking test according to ASTM
176 D5117-09 (2009). Five specimens 25 mm in length for each bar diameter were placed into a dye
177 penetrant solution from a mixture of basic fuchsin ($\text{C}_{20}\text{H}_{19}\text{N}_3\text{HCl}$) and methyl hydrate with a
178 1:100 weight ratio. The wicking action is revealed by the apparition of spots on the side of the
179 specimen not immersed in the solution. The tests were made at a room temperature and relative
180 humidity of 23°C and 50%, respectively. Before the test, a precautionary nail-polish shield
181 recommended by ASTM D2374-05 (2011) was applied in order to prevent wicking along the bar
182 periphery. The dye penetrant solution is poured in a disposable pan so that only the bottom three
183 mm of the specimens is immersed. The presence and number of the colored dots were then noted

184 after 15 minutes of immersion. No colored dots were observed in any of the specimens,
185 indicating that there were no voids or cracks running through the length of the bars. As specified
186 in CSA 807 (2010), the void content in FRP bars should be no greater than 1%.

187 **Water Absorption**

188 The water absorption of the bars after 24 hours and at saturation was determined according to
189 ASTM D 570-98 (2010). Nine specimens 75 mm in length were prepared, dried, and weighed for
190 each bar diameter. These specimens were then entirely immersed in distilled water at 60°C. The
191 samples were removed from the water after 24 hours, surface dried, and weighed. Then, they
192 were placed in water again until full saturation, i.e., when the weight increase in three
193 consecutive weightings was less than 1%. In calculating the water absorption, the loss of sand
194 coating was considered by weighing the specimens two times, i.e., just after removing the
195 specimens from water and after 24h of oven drying at 60°C. The difference between the two
196 measurements gave the real mass of absorbed water.

197 The water absorption of the GFRP bars at 24 hours and at saturation was found to decrease as
198 the diameter of the bars increased. The maximum absorption of the #3 bars after 24 hours and at
199 saturation was 0.152% and 0.195%, respectively. This low water absorption for the GFRP bars
200 considered herein—even at saturation—is due to the low moisture diffusion of the vinylester
201 resin, as indicated by Tannous and Saadatmanesh (1999). For FRP reinforcing bars, the limit of
202 water absorption after 24 hours specified in CSA-S807 (2010) is 0.25%. The values at saturation
203 are 1% and 0.75% (high durability) in ACI 440.6M (2008) and CSA-S807 (2010), respectively.
204 This shows that the water absorption of the GFRP bars with different diameters is well within the
205 allowable specified limit in current standards.

206

207 **Cure Ratio (%) and Glass Transition Temperature (T_g)**

208 The cure ratio and glass transition temperature, T_g , of the GFRP bars were determined by
209 differential scanning calorimetry (DSC) according to the ASTM E 1356-08 (2014) test method.
210 For this test, nine pieces weighing about 20 mg were cut from the center of the core of each bar,
211 weighed, and placed in an aluminum pan. The specimens were then heated from 25°C to 180°C
212 at a rate of 10°C/min. The T_g obtained for all bar diameters ranged from 105°C to 125°C for the
213 GFRP bar, which is higher than the limit of 100°C specified in CSA S807 (2010) and ACI
214 440.6M (2008). Similarly, a cure ratio of 100% was measured for all bar diameters. It is worth
215 noting that the specified cure ratio for GFRP bars is only 95% (CSA S807, 2010).

216 **MECHANICAL PROPERTIES OF THE GFRP BARS**

217 The mechanical properties of the unconditioned (reference) and conditioned GFRP bars with
218 different diameters were assessed under three-point flexural testing, short-beam shear testing,
219 and tensile testing. Due to the limited length of both the conditioned and unconditioned #6 GFRP
220 bar specimens provided by the industry partner, there were no remaining portions to conduct the
221 flexural testing for this bar size. Table 3 summarizes the results of the mechanical
222 characterization. The values listed within parentheses are the standard deviation of the test
223 results. The nominal diameter and nominal cross-sectional area of the GFRP bars were used in
224 calculating the mechanical properties.

225 **Flexural Properties**

226 Flexural testing was conducted for comparative assessment of the mechanical properties of the
227 FRP bars. The test was conducted in accordance with ASTM D4476/D4476M-14 (2014). The
228 unconditioned and conditioned specimens were tested over a simply supported span equal to 20
229 times the bar diameter and with an overhang twice the bar diameter at each support. Six

230 replicates for each bar diameter were tested under laboratory conditions on an MTS 810 testing
231 machine equipped with a 500 kN load cell. The specimens were loaded at the midspan with a
232 circular nose and supported at the ends on two circular supports that allowed the specimens to
233 bend, as shown in Figure 2a. A displacement control rate of 3.0 mm/min was used. The applied
234 load and deflection were recorded during the test with a data acquisition system monitored by a
235 computer. The flexural strength of the GFRP bars, f_u , in the outermost fibers at midspan was
236 calculated as $f_u = PLc/(4I)$, where P is the failure load, L is the clear span, c is the distance to
237 the centroid of the extreme-most fibers, and I is the moment of inertia.

238 Under bending, the load–deflection behavior of all the specimens (Figure 3a) showed linear
239 behavior, but a slight reduction in stiffness was observed before final failure. This reduction of
240 stiffness is due to the initiation of compressive failure under the loading point, which is more
241 noticeable in the conditioned specimens than the reference samples. Moreover, the conditioned
242 samples failed at lower load and deflection than the reference samples, but with the same
243 bending stiffness prior to failure. Regardless of diameter, the bars failed due to compression in
244 the top fibers, followed by tensile failure at the bottom near the midpoint of the specimens
245 (Figures 3b and 3c).

246 **Interlaminar Shear-Strength Properties**

247 The short-beam shear testing was conducted following ASTM D4475-02 (2016) in order to
248 determine the interlaminar shear strength of FRP bars (Figure 2b). The short-beam shear test is a
249 matrix-dominated property and can give an indication of the resistance of the fiber–matrix
250 interface. The test was carried out with MTS 810 testing machine equipped with a 500 kN load
251 cell. Six replicates for each bar diameter were prepared and tested. The distance between the
252 shear planes was set to six times the nominal diameter of the FRP bars. A displacement control

253 rate of 1.3 mm/min was employed for the #3, #4, and #5 bars, while 1.8 mm/min was used for
254 the #6 and #8 bars. The applied load and displacement were recorded with a computer-monitored
255 data-acquisition system. The interlaminar shear strength S_u of the FRP bar was calculated as
256 $S_u = 0.849P/d^2$, where P is the shear failure load and d is the bar diameter.

257 Figure 4 shows the results from short-beam shear testing. It can be seen that the applied load
258 increased linearly with the deflection with a slight nonlinearity before the final failure. This
259 nonlinear behavior before final failure is more apparent in the larger diameter bars. The
260 experimental results also show that the conditioned specimens failed at a lower load than the
261 reference samples. Micelli and Nanni (2004) indicated that the decrease in the apparent
262 horizontal shear strength of the conditioned GFRP bars is caused by resin damage due to
263 penetration of the alkaline solution. Both the unconditioned and conditioned specimens failed
264 due to horizontal shear cracks that originated from the edge of the bars and developed along the
265 length (Figures 4b and 4c). Park et al. (2008) indicated that very high interlaminar-shear stresses
266 can arise at the free edge of fiber composite materials. The only observed difference was the
267 more obvious compressive failure under the loading point and at the supports that occurred with
268 the larger diameter bars. This is due to the higher load needed to cause failure of the larger
269 diameter bars and achieve the same level of interlaminar shear stress, while the contact area
270 under the loading point was almost the same for all of the bar sizes. This observation explains the
271 nonlinear behavior of the bars before the final failure.

272 **Tensile Properties**

273 Tensile testing was conducted according to ASTM D7205/D7205M-06 (2011) and CSA-S806-12
274 Annex C. The tensile testing along the alignment of fibers is related to fiber properties. The
275 gauge length of the specimens was approximately equal to 40 times the bar diameter, in addition

276 to the length of the anchorage steel tubes at each end of the GFRP bars, as specified in CSA-
277 S806-12, Annex B. Table 4 provides the specimen and anchor length for each bar size. Each
278 specimen was instrumented with two LVDTs 200 mm in length to capture specimen elongation
279 during testing (Figure 1c). To avoid damaging the LVDTs, they were detached from the
280 specimen when the load reached 75% of the estimated ultimate load. The tests were carried out
281 with a Satec-Baldwin testing machine equipped with a 2000 kN load cell. The load was
282 increased at a rate of 300 MPa/min until tensile failure occurred. Six specimens were tested for
283 each bar diameter. The applied load and bar elongation were electronically recorded during the
284 test with a computerized data-acquisition system. This test determined the ultimate tensile
285 strength f_t , tensile modulus E and tensile strain ε .

286 The typical stress strain behavior of the GFRP bars with different diameters is shown in
287 Figure 5a. All of the specimens behaved in a linear elastic fashion in tension up to failure and
288 exhibited almost identical slopes in the stress–strain curve. It is to be noted that the strain after
289 the LVDT's were removed was calculated based on the stress and elastic modulus of the bars.
290 This behavior indicates that the elastic moduli of the bars with different diameters were similar
291 and that the loss of elastic modulus due to exposure to the simulated alkaline environment was
292 negligible. Nevertheless, the failure stress and rupture strain of the conditioned bars were lower
293 than that of the reference bars. Robert et al. (2009) had similar findings and they indicated that
294 the elastic modulus of the GFRP bars they tested was not affected by aging in a concrete
295 environment, but tended to be more brittle and evidenced lower strength than the reference bars.
296 Generally, rupture strain decreases as bar diameter increases. Figures 5b and 5c show that,
297 regardless of diameter, the GFRP bars tested failed at the middle of the bar (within the gauge
298 length). All of the specimens failed suddenly, as expected, due to tensile fiber rupture. Prior to

299 failure, a popping noise was heard caused by some of the fibers and/or the resin failing on the
300 outer perimeter of the bar. It is important to note that the measured tensile strength for both the
301 reference and conditioned bars (all bar diameters) was significantly higher than 655 MPa and
302 750 MPa, and that their elastic moduli were 39.3 GPa and 60 GPa, as specified in ACI 440.6M
303 and CSA S807-10, respectively for high modulus GFRP bars. Similarly, the failure strain was
304 higher than the prescribed 1.2%.

305 **DISCUSSION**

306 The effects of bar diameter on physical, mechanical, and durability properties are analyzed and
307 discussed in this section.

308 **Effect of Bar Diameter on Physical Properties**

309 The bar diameter had no significant effect on most of the physical properties of the GFRP bars,
310 including the transverse coefficient of thermal expansion, porosity, and T_g . Similarly, all of the
311 bars tested evidenced an entirely cured resin, indicating that bar diameter did not affect the
312 degree of cure. The development of an efficient production method makes this consistency
313 possible. This is in contrast with the observations made by Yi and Hilton (1988), who indicated
314 that laminate thickness might affect the degree of cure due to the higher thermal conductivity of
315 thicker composite laminates. On the other, the fiber content and water absorption were found to
316 increase and decrease, respectively, with increasing bar diameter. Since none of the FRP bars
317 contained voids, the lower water absorption for the larger diameter bars can be correlated to
318 increasing fiber content (by weight), as noted in section 2.4.1. Glass fibers absorb scarcely any
319 water, therefore the bars with higher matrix contents evidenced higher absorption rates.

320 In order to further correlate bar diameter to the percentage water absorption, the shape ratio of
321 the GFRP bars were calculated and plotted (see Figure 6). Cinquin and Medda (2009) defined the

322 shape ratio as the ratio between the sample's surface and volume. As can be seen in Figure 6a,
323 the shape ratio was significant in the water absorption of the GFRP bars at 24 hours (24 h) and at
324 saturation (*Saturation*), i.e., the water absorption increased as did the shape ratio. It can also be
325 observed that the relationship between the water absorption at 24 hours (%) and at saturation to
326 that of the shape ratio is the same, as demonstrated by the almost equal slopes of the water
327 absorption and shape-ratio relationship curves. On the another hand, there is a linear but negative
328 correlation between the shape ratio and bar diameter. The shape ratio decreases as the bar
329 diameter increases. This accounts for the smaller diameter bars having higher absorption rates
330 than the larger diameter ones with the same length, since the exposed surface is greater with
331 respect to volume. It is also worth noting that the decrease in the shape ratio is very similar to the
332 decrease in the percentage of water absorption at saturation (%) for the various bar diameters.

333 **Effect of Bar Diameter on Mechanical Properties**

334 Many studies have revealed that the short-term mechanical properties of FRP bars decrease with
335 increased bar diameter (Bank 2006; Hollaway 2008). This conclusion, however, was not clearly
336 observed in our study. Figure 7 shows the normalized mechanical properties for the different
337 sizes of GFRP bars. This graph provides the percentage of the interlaminar shear strength (*ILSS*),
338 flexural strength (*Flexure*), tensile strength (*Tensile*), and tensile modulus (*Modulus*) for all of
339 the bar diameters with respect to the mechanical properties of the #3 bars. The figure show no
340 significant difference in the tensile properties of the GFRP bars regardless of bar diameter. While
341 the highest tensile strength and modulus were observed for the #3 bars, the lowest tensile
342 properties were exhibited by the #5 bars (94% compared to the #3 bars), with the #8 bars
343 exhibiting more than 96% of strength and stiffness of the #3 bars. Kocaoz et al. (2005) suggested
344 that modulus, which is an intrinsic property of the material, is not significantly affected by bar

345 cross-sectional size but rather by the level of fibers contained in the bar. Since the percentage
346 fiber content by weight (%) (Table 2) for different bar diameters was almost the same, then the
347 bars should record the same elastic modulus. Moreover, the consistency in the measured tensile
348 properties of the GFRP bars with different diameters can be due to an adequate anchor length,
349 which resulted in a more efficient transfer of stresses from the bar surface to the center. Portnov
350 and Bakis (2008) suggested that introducing a more uniform distribution of the applied shear
351 stress near the grips could minimize the shear lag effect and increase the tensile-load-carrying
352 capacity of round pultruded rods.

353 In contrast to the tensile properties, there was a size effect observed for ILSS and flexural
354 strength. The #8 bars recorded ILSS and flexural strength almost 14% lower than the #3 bars.
355 Significant size effects were also observed by Wisnom and Jones (1996) on the average ILSS for
356 unidirectional glass-fiber/epoxy composites. They indicated that the lower ILSS with bigger
357 specimens could be due to the larger inherent defects. Koller et al. (2007) also suggested that the
358 probability of having large defects in composite materials increases with increased specimen
359 volume. Moreover, it should be noted that ILSS is a matrix-dominated property. Wisnom and
360 Jones (1996) suggested that matrix-dominated failures show the largest size effects in composite
361 materials. Defects near the edge of the GFRP bars were very critical for the specimens subjected
362 to the short-beam test as this location is subjected to higher levels of shear stress. Similarly, the
363 lower flexural properties of the larger diameter bars can be explained by the high probability of
364 defects. Carvelli et al. (2009) suggested that it is more difficult to keep the filaments parallel to
365 one another in larger diameter FRP bars during the pultrusion process, increasing their tendency
366 to buckle under compression. This is, in fact, the failure mechanism observed in the GFRP bars

367 during the flexural test, in which the failure was initiated by the compression buckling of the top
368 fibers.

369 **Property Retention of GFRP bars with Different Diameters**

370 Tannous and Saadatmanesh (1999) indicated that the effect of an alkaline solution on FRP bars
371 only involved a very thin layer on the exposed surface. Thus, the approximate layer thickness
372 and area of the GFRP bars affected by the alkaline solution were calculated and reported in Table
373 5 to correlate with the property retention for different bar diameters. These values were
374 determined by assuming that the affected portions of the GFRP bar were the same as the
375 percentage of water absorption at saturation (%) and equally distributed along the surface of the
376 bars (Table 2). This approach was similar to the method adopted by Cinquin and Medda (2009).
377 It can be clearly seen that the affected thickness is only in the order of 1.9×10^{-3} to 5.4×10^{-3}
378 mm. Moreover, the percentage of affected thickness with respect to the nominal diameter
379 decreased as did bar diameter.

380 Figure 8 provides the strength and stiffness retention properties of the GFRP bars with
381 different diameters. Figures 8a to 8c clearly indicate that the strength properties were affected by
382 conditioning in the alkaline solution, while Figure 8d shows that the modulus of elasticity was
383 not affected. The almost 100% retention of the modulus of elasticity, which is a fiber-dominated
384 property, for all bar diameters indicates that the damage caused by the moisture diffusion was
385 confined to the very thin layer of the exposed surface and that the reinforcing fibers were not
386 affected by the conditioning. As the modulus of elasticity was determined from the linear-elastic
387 portion of the stress and strain curve, the matrix was still effectively transferring stresses to the
388 fibers. Nkurunziza et al. (2005) indicated that the diffusion of moisture and alkalis in composites
389 can destroy the bond between the fiber and matrix, damaging the interface. This is difficult to see

390 at lower loads, but higher mechanical loads increase the degradation of the fiber–matrix
391 interface. This accounts for the noticeable decrease in strength properties, as these values were
392 calculated at the point of failure of the GFRP bars at which the stress distribution along the fibers
393 is less uniform.

394 Figures 8a shows that the effect of conditioning on the ILSS of the GFRP bars was significant
395 with the smaller diameter bars, but decreased as the diameter increased. In fact, the residual
396 horizontal shear strength for the #8 bars was the same as that measured on the reference bars,
397 while the #3 bars retained only 88% of their ILSS. This can be explained by the thinner layer
398 affected by the alkaline solution in the case of the larger diameter bars, as reported in Table 5. As
399 indicated in the previous section, ILSS is governed by the fiber–matrix interface. Thus, the
400 decrease in ILSS can be correlated to interface degradation. Similarly, due to the very thin layer
401 affected by conditioning in the alkaline solution in the larger diameter GFRP bars, its affected
402 area was also significantly smaller with respect to the total area, compared to the smaller
403 diameter bars.

404 Figure 8b shows that the flexural-strength retention increased with bar diameter. The retention
405 ranged from 88% retention for the #3 bars to more than 97% for the #8 bars. This behavior was
406 also observed by Maranan et al. (2014), who found that larger diameter bars exhibited a slower
407 rate of strength degradation at high temperature than small diameter bars. Cinquin and Medda
408 (2009) also concluded that the residual mechanical properties were more affected in thin
409 composites than thick composites. The higher flexural strength retention for the larger diameter
410 bars could be due to the strength gradient through bar diameter during bending. During flexural
411 tests, the outermost fibers are subject to the maximum stress. Thus, a smaller amount of fibers
412 with respect to the total volume was under the maximum stress in the larger diameter bars.

413 Moreover, the higher flexural-strength retention in the larger diameter bars can be correlated to
414 the smaller reduction in the second moment of area of the conditioned specimens. Since only the
415 bar surface was damaged, the fibers and matrix in the intact zone were undamaged and had the
416 same initial mechanical properties, resulting in a better redistribution of load when the outer
417 fibers progressively failed.

418 Figure 8c shows a opposite trend than do Figures 8a and 8b, in which the smaller diameter
419 bars exhibited higher tensile-strength retention. This figure shows that the #3 bars retained more
420 than 95% of their tensile strength, while the #8 bars retained only 88%. This trend can be due to
421 the shear lag effect. Achillides and Pilakoutas (2004) indicated that larger diameter FRP bars had
422 more significant shear lag-effect than smaller diameter bars and had a noticeable effect on tensile
423 strength. Castro and Carino (1998) further mentioned that the efficiency of the stress transfer
424 from the bar surface to the interior fibers influences the mechanical properties of the FRP bars.
425 Due to the shear lag effect, the outer fibers experience higher stresses than the inner fibers, even
426 though all fibers resist the tensile load at the same time. Due to conditioning in alkaline solution,
427 the outer surface of the bars was affected and might have decreased mechanical properties. As
428 the specimens were loaded, the outer fibers— which were subjected to higher stress—initiated
429 failure and the breakage moved instantly to the inner fibers, leading to the sudden and
430 catastrophic failure of the GFRP bars. This also explains the reason why the tensile strength is
431 more affected by the conditioning than the interlaminar shear and flexural strength.

432 From the above results, it can be concluded that the conditioning in alkaline solution affected
433 the flexural, ILSS, and tensile strength properties of the GFRP bars, but not their moduli of
434 elasticity. Moreover, the strength-retention limit was affected by bar size. The ILSS and flexural
435 strength of the smaller diameter bars was affected more than the larger diameter ones. This is in

436 contrast to tensile strength: the larger diameter bars had lower tensile strength retention. These
437 results suggest that the conclusions drawn by most studies based on smaller diameter FRP bars
438 do not apply to larger diameters. Based on the results in this study, it is more reasonable to use
439 larger diameter bars in assessing the tensile-strength retention of FRP bars exposed to severe
440 environmental conditions. Nevertheless, note should be taken of the very high load required to
441 cause failure of larger bars. That notwithstanding, the strength retention in all the bar diameters
442 considered in this study is significantly higher than the 0.70 environmental reduction coefficient
443 required by several codes.

444 **SEM AND FTIR OBSERVATIONS**

445 Scanning-electron-microscopy (SEM) observations were performed to assess the microstructure
446 of the GFRP bars before and after conditioning. All of the specimens observed under SEM were
447 cut, polished, and coated with a thin layer of gold–palladium using a vapor-deposit process.
448 Microstructural observations were performed on a JEOL JSM-840A SEM. Similarly, Fourier
449 Transformed Infrared Spectroscopy (FTIR) was conducted for each bar diameter to study the
450 changes in the chemical composition of the matrix at the bar surface. These observations were
451 conducted to determine the potential degradation of the polymer matrix, glass fibers, or interface,
452 as applicable, due to the penetration of the alkaline solution. The aim was to link these
453 observations to the possible evolution of mechanical properties and chemical composition of the
454 bars after conditioning.

455 **SEM**

456 Figures 9 and 10 show the SEM micrographs of the cross section of the reference and
457 conditioned GFRP bars, respectively. As shown in Figures 9a and 9b, there were no pores
458 observed in the center or near the surface of the reference bars. There was also no noticeable gap

459 at the fiber–matrix interface, indicating excellent adhesion between the fibers and matrix. This is
460 also true in the center of the conditioned GFRP bars (Figure 10a). Small gaps between the fibers
461 and matrix were observed near the exposed surface in some conditioned specimens (Fig. 10b),
462 suggesting that the bars were affected after exposure to the alkaline solution. This damage to the
463 fiber–matrix interface reduces the transfer of loads between fibers and results in the reduction in
464 strength properties. Benmokrane et al. (2002), however, indicated that the mechanical properties
465 of GFRP bars are controlled by the fiber component. If the fibers have not deteriorated, FRP bars
466 will preserve most of their mechanical strength and will be able to support loads. If the protective
467 resin degrades, the bonding between the matrix and fibers located on the outer part of the bar will
468 gradually reduce and bar resistance will start to decrease. This is the most probable reason why
469 the flexural, ILSS, and tensile strength properties of GFRP bars decreased after alkaline
470 conditioning for 3 months. Nevertheless, the strength reduction is small as the SEM observation
471 confirmed that only the exposed surface of the GFRP bars was affected, not the core section.
472 This exposed surface can be considered as being an "all-resin" surface, which does not contribute
473 much in resisting the applied tensile load.

474 **FTIR**

475 Figure 11 shows the infrared spectroscopy (FTIR) spectra of the surface of the reference and
476 conditioned GFRP bars. Only the FTIR for the #3 and #8 bars are provided for comparison. The
477 FTIR for both bar diameters shows no clear differences between the infrared spectra of the
478 reference and conditioned GFRP bars. Moreover, the FTIR did not show any significant changes
479 in the chemical structure after exposure to the alkaline solution. These observations indicate that
480 the surface of the bars exposed to the alkaline solution for 3 months at 60°C had not been
481 chemically modified and might possess the same initial mechanical properties. These results

482 further confirm that the degradation of the matrix remains only at the exposed surface of the
483 GFRP bars. This supports the findings by Nkurunziza et al. (2005) that vinylester epoxies are
484 very resistant to chemical attack, which improves the environmental resistance of FRP bars made
485 with these resins.

486 **CONCLUSIONS**

487 The effects of diameter on the physical, mechanical, and durability properties of sand-coated
488 GFRP bars made of continuous boron-free glass fibers (EC-R) impregnated in a vinylester-based
489 resin matrix were investigated. Based on the results of this study, the following conclusions
490 were drawn for the tested GFRP bars:

- 491 • With the bar sizes considered, bar diameter did not affect fiber content, transverse coefficient
492 of thermal expansion, porosity, or glass transition temperature. On the other hand, the water
493 absorption was found to decrease as the diameter increased. This can be correlated to the
494 ratio of the surface area to the volume (shape ratio) of the GFRP bars.
- 495 • The tensile strength and modulus of the reference bars were not significantly affected by the
496 cross-sectional size, but a size effect was observed for interlaminar shear strength and
497 flexural strength. The consistency in the measured tensile properties for GFRP bars with
498 different diameters is due to the efficient stress transfer from the bar surface to the center. On
499 the other hand, the higher probability of defects contained in the larger diameter bars may
500 have caused the lower interlaminar shear strength and flexural strength in comparison to the
501 smaller diameter bars.
- 502 • The elastic moduli of the reference and conditioned bars were same for all bar diameters,
503 which is due to nearly same fiber content of the GFRP bars.

- 504 • The interlaminar shear strength and flexural strength of the larger diameter GFRP bars were
505 less affected after exposure to the alkaline solution than the smaller bar diameter. The higher
506 interlaminar shear and flexural strength retention for the larger bar sizes was due to the lower
507 affected thickness. As a result, the penetrated area was proportionally small relative to the
508 total cross-sectional area of the bar.
- 509 • The tensile-strength retention was highest for the smallest diameter bar. This suggests that
510 the impact of conditioning on the tensile properties of GFRP bars is expected to be greater
511 for larger than smaller diameters.
- 512 • The scanning-electron-microscope and FTIR observations showed no changes in the material
513 properties and chemical structure in the exposed surface of the bars after conditioning in the
514 alkaline solution for 90 days at 60°C. This shows that the degradation remained at the surface
515 for all the bar diameters.

516 Nevertheless, the variations in the physical and mechanical properties of the GFRP bars
517 investigated in this study, from one diameter to another, remained low. Thus, the suggestions of
518 the current standards and specifications to not relate the strength-retention limit to the size of the
519 FRP bars are acceptable. Further research, however, is needed to investigate other bar types and
520 diameters to clearly determine how the diameter might affect the design of GFRP-reinforced
521 concrete structures.

522 **ACKNOWLEDGMENTS**

523 The authors would like to acknowledge the support of the Natural Sciences and Engineering
524 Research Council of Canada (NSERC), NSERC Research Chair in Innovative FRP
525 Reinforcement for Concrete Infrastructures, The Fonds Québécois de la Recherche sur la Nature
526 et les Technologies (FQR-NT), and Pultrall Inc. (Thetford Mines, Quebec) for the GFRP

527 materials support. The technical assistance from the staff of the Structural Laboratory in the
528 Department of Civil Engineering, Faculty of Engineering at the University of Sherbrooke, are
529 also acknowledged. The second author also acknowledges the scholarship granted by the
530 Australian Government Endeavour Research Fellowships to undertake his research and
531 professional development at the University of Sherbrooke.

532 **REFERENCES**

533 Ahmed, E., Benmokrane, B., and Sansfaçon, M. (2016). "Case Study: Design, Construction, and
534 Performance of the La Chancelière Parking Garage's Concrete Flat Slabs Reinforced with GFRP
535 Bars." *ASCE Journal of Composites for Construction*, DOI: 10.1061/(ASCE)CC.1943-

536 5614.0000656

537 American Concrete Institute (2008). Metric specification for carbon & glass fiber-reinforced
538 polymer bar materials for concrete reinforcement. ACI-440.6M-08, Farmington Hills, Michigan,
539 USA.

540 American Concrete Institute (2012). Guide test methods for fiber-reinforced polymer, ACI
541 440.3R-12, Farmington Hills, Michigan, USA.

542 American Concrete Institute (2015). Guide for the design and construction of concrete reinforced
543 with FRP bars, ACI 440.1R-15, Farmington Hills, Michigan, USA.

544 Arafa, A., Farghaly, A., Ahmed, E., Benmokrane, B. (2016). "Testing of GFRP-RC Panels with
545 UHPRFC Joints of Nipigon River Cable Stayed Bridge in Northwest Ontario, Canada." *ASCE*
546 *Journal of Bridge Engineering*, DOI: 10.1061/(ASCE)BE.1943-5592.0000943, p. 05016006-1-
547 05016006-14.

548 Archillides, Z. and Pilakoutas, K. (2004). "Bond behaviour of fibre reinforced polymer bars
549 under direct pullout conditions." *Journal of Composites for Construction*, 8(2), 173-181.

550 ASTM Standard D570 – 98 (2010). Standard test method for water absorption of plastics. *ASTM*
551 *D570 – 98*, ASTM International, West Conshohocken, Philadelphia, Pa 19103.

552 ASTM Standard D2374-05 (2011). Standard test method for lead in paint driers by EDTA
553 Method. *ASTM D2374-05*, ASTM International, West Conshohocken, Philadelphia, Pa 19103.

554 ASTM Standard D3171-15 (2015). Standard test methods for constituent content of composite
555 materials. *ASTM D3171–15*, ASTM International, West Conshohocken, Philadelphia, Pa 19103.

556 ASTM Standard D4475-02 (2016). Standard test method for apparent horizontal shear strength
557 of pultruded reinforced plastic rods by the short-beam method. *ASTM D4475-02*, ASTM
558 International, West Conshohocken, Philadelphia, Pa 19103.

559 ASTM Standard D4476/D4476M - 14(2014). Standard test method for flexural properties of
560 fiber reinforced pultruded plastic rods. *ASTM D4476/D4476M-14*, ASTM International, West
561 Conshohocken, Philadelphia, Pa 19103.

562 ASTM Standard D5117-09 (2009). Standard test method for dye penetration of solid fiberglass
563 reinforced pultruded stock. *ASTM D5117 – 09*, ASTM International, West Conshohocken,
564 Philadelphia, Pa 19103.

565 ASTM Standard D7205/D7205M-06 (2011). Standard test method for tensile properties of fiber
566 reinforced polymer matrix composite bars. *ASTM D7205/D7205M-06*, ASTM International,
567 West Conshohocken, Philadelphia, Pa 19103.

568 ASTM Standard D7705/D7705M - 12(2012). Standard test method for alkali resistance of Fiber
569 Reinforced Polymer (FRP) matrix composite bars used in concrete construction. *ASTM*
570 *D7705/D7705M-12*, ASTM International, West Conshohocken, Philadelphia, Pa 19103.

571 ASTM Standard E1131-08(2014). Standard test method for compositional analysis by
572 thermogravimetry. *ASTM E1131-08*, ASTM International, West Conshohocken, Philadelphia, Pa
573 19103.

574 ASTM Standard E1356-08(2014). Standard test method for assignment of the glass transition
575 temperatures by differential scanning calorimetry. *ASTM E1356-08*, ASTM International, West
576 Conshohocken, Philadelphia, Pa 19103.

577 Bakis, C. E. (1993) "FRP Composites: Materials and Manufacturing." *Fiber-Reinforced-Plastic*
578 *for Concrete Structures: Properties and Applications*, A. Nanni, ed., Elsevier, Amsterdam, pp.
579 13-58.

580 Bakis, C. E., Freimanis, A. J., Gremel, D., and Nanni, A. (1998) "Effect of resin material on
581 bond and tensile properties of unconditioned and conditioned FRP reinforcement rods."
582 *Proceedings of the First International Conference on Durability of Composites for Construction*,
583 B. Benmokrane and H. Rahman, eds., Sherbrooke, QC, Canada, pp. 525-535.

584 Bank, L.C. (2006). *Composites for construction: Structural design with FRP materials*, John
585 Wiley and Sons, Inc., New Jersey.

586 Belarbi, A., and Wang, H. (2012) "Durability of FRP bars embedded in fiber-reinforced-
587 concrete," *Journal of Composites for Construction*, 16(4), pp. 371-380.

588 Benmokrane, B., and Rahman, H., eds. (1998) "Durability of Fiber Reinforced Polymer (FRP)
589 composites for construction," *Proceedings of the First International Conference (CDCC '98)*,
590 QC, Canada, 692 pp.

591 Benmokrane, B., Wang, P., Ton-That, T., Rahman, H., and Robert, J.F. (2002). "Durability of
592 glass fibre reinforcing bars in concrete environment." *Journal of Composites for Construction*,
593 6(3), 143-153.

594 Benmokrane, B., El-Salakawy, E., El-Ragaby, A., and Lackey, T. (2006). "Designing and testing
595 of concrete bridge decks reinforced with glass FRP bars." *Journal of Bridge Engineering*, 11(2),
596 217-229.

597 Benmokrane, B., Elgabbas, F., Ahmed, E., and Cousin, P. (2015). "Characterisation and
598 comparative durability study of glass/vinylester, basalt/vinylester, and basalt/epoxy FRP bars."
599 *Journal of Composites for Construction*, 19(6):04015008, 1-12.

600 Canadian Standards Association (CSA). (2010). "Specification for fibre-reinforced polymers."
601 CAN/CSA-S807, Rexdale, Ontario, Canada.

602 Canadian Standards Association (CSA). (2012). "Design and construction of building structures
603 with fibre-reinforced polymers." CAN/CSA-S806-12, Rexdale, Ontario, Canada.

604 Canadian Standards Association (CSA). (2006-Edition 2014). "Canadian highway bridge design
605 code—Section 16, updated version for public review." CAN/CSA-S6-14, Rexdale, Ontario,
606 Canada.

607 Carvelli, V., Giulia, F., and Pisani, M.A. (2009) "Anchor system for tension testing of large
608 diameter GFRP bars." *Journal of Composites for Construction*, 13(5), 344-349.

609 Castro, P.F. and Carino, N.J. (1998) "Tensile and non-destructive testing of FRP bars." *Journal*
610 *of Composites for Construction*, 2(1), 17-27.

611 Chen, Y., Davalos, J. F., Ray, I., and Kim, H.-Y. (2007) "Accelerated aging tests for evaluations
612 of durability performance of FRP reinforcing bars for concrete structures." *Composite*
613 *Structures*, 78(1), 101-111.

614 Cinquin, J., and Medda, B. (2009) "Influence of laminate thickness on composite durability for
615 long term utilisation at intermediate temperature (100 - 150°C)." *Composites Science and*
616 *Technology*, 69, 1432-1436.

617 Drouin, B., Latour, G., and Mohamed, H. (2011) "More than 10 years successful field
618 applications of FRP bars in Canada." *CDCC 2011, The Fourth International Conference on*
619 *Durability & Sustainability of Fiber Reinforced Polymer (FRP) Composites for Construction*
620 *and Rehabilitation*, Quebec City, QC, Canada, 6 pp.

621 *fib*, (2007) "FRP Reinforcement in RC Structures" Bulletin No. 40, Federal Institute of
622 Technology, Lausanne, Switzerland.

623 Hollaway, L.C. (2008). "Advanced fibre polymer composite structural systems used in bridge
624 engineering." *ICE Manual of Bridge Engineering*, 503-529.

625 Hollaway, L.C. (2010). "A review of the present and future utilisation of FRP composites in the
626 civil infrastructure with reference to their important in-service properties." *Construction and*
627 *Building Materials*, 24, 2419-2445.

628 Kamal, A., and Boulfiza, M., (2011) "Durability of GFRP rebars in simulated concrete solutions
629 under accelerated aging conditions." *Journal of Composites for Construction*, 15(4), pp. 473-
630 481.

631 Kocaoz, S., Samaranayake, V.A., and Nanni, A. (2005). "Tensile characterization of glass FRP
632 bars." *Composites: Part B*, 36, 127-134.

633 Koller, R., Chang, S. and Xi, Y. (2007). "Fiber-reinforced bars under freeze-thaw cycles and
634 different loading rates." *Journal of Composite Materials*, 41(1), 5-25.

635 Manalo, A.C., Benmokrane, B., Park, K., and Lutze, D. (2014). "Recent developments on FRP
636 bars as internal reinforcement in concrete structures". *Concrete in Australia*, 40(2), 46-56.

637 Maranan, G.B., Manalo, A.C., Karunasena, W., Benmokrane, B., and Lutze, D. (2014). "Flexural
638 behaviour of glass fibre reinforced polymer (GFRP) bars subjected to elevated temperature".

639 *Proc. 23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*,
640 Byron Bay, Australia, 187-192.

641 Micelli, F., and Nanni, A. (2004). "Durability of FRP rods for concrete structures." *Construction*
642 *and Building Materials*, 18, 491-503.

643 Mohamed, H.M., and Benmokrane, B. (2014). "Design and Performance of Reinforced Concrete
644 Water Chlorination Tank Totally Reinforced with GFRP Bars." *ASCE Journal of Composites for*
645 *Construction*, Vol. 18, No.1, pp. 05013001-1 – 05013001-11

646 Mohamed, H. M., and Benmokrane, B. (2015). "Make the Case: The Use of FRP Bars for Soft-
647 Eyes in Construction of Tunnels." *Tunnels and Tunneling, The official publication of the*
648 *Tunneling Association of Canada*, Dec.-Jan., pp. 35-40.

649 Nkurunziza, G., Debaiky, A., Cousin, P., and Benmokrane, B. (2005). "Durability of GFRP bars:
650 A critical review of the literature." *Progress in Structural Engineering and Materials*, 7(4), 194–
651 209.

652 Park, C., Jang, C., Lee, S., and Won, J. (2008). "Microstructural investigation of long-term
653 degradation mechanisms in GFRP dowel bars for jointed concrete pavement." *Journal of Applied*
654 *Polymer Science*, 108(5), 3128 -3137.

655 Porter, M. L., Mehus, J., Young, K. A., O'Neil, E. F., and Barnes, B. A. (1997) "Aging for Fiber
656 Reinforcement in Concrete," *Proceedings of the Third International Symposium on Non-Metallic*
657 *(FRP) Reinforcement for Concrete Structures (FRPRCS-3)*, V. 2, Japan Concrete Institute,
658 Tokyo, Japan, pp. 59-66.

659 Portnov, G. and Bakis, C.E. (2008). "Analysis of stress concentration during tension of round
660 pultruded composite rods." *Composite Structures*, 83, 100-109.

661 Pultrall (2012). V-ROD FRP reinforcing bars data sheet. Website:
662 [http://www.vrodcanada.com/sites/default/files/pdfs-uploaded/V-](http://www.vrodcanada.com/sites/default/files/pdfs-uploaded/V-ROD%2060GPa%20Grd%20III%20Std%20-%20Oct%202012.pdf)
663 [ROD%2060GPa%20Grd%20III%20Std%20-%20Oct%202012.pdf](http://www.vrodcanada.com/sites/default/files/pdfs-uploaded/V-ROD%2060GPa%20Grd%20III%20Std%20-%20Oct%202012.pdf)
664 Robert, M., and Benmokrane, B. (2013) “Combined effects of saline solution and moist concrete
665 on long-term durability of GFRP reinforcing bars.” *Journal of Construction and Building*
666 *Materials*, 38, pp. 274-284.
667 Robert, M., Cousin, P., and Benmokrane, B. (2009). “Durability of GFRP reinforcing bars
668 embedded in moist concrete.” *Journal of Composites for Construction*, 13(2), 66-73.
669 Tannous, F.E. and Saadatmanesh, H. (1999). “Durability of AR glass fibre reinforced plastic
670 bars.” *Composites for Construction*, 3(1), 12-19.
671 Wisnom, M.R. and Jones, M.I. (1996). “Size effects in interlaminar tensile and shear strength of
672 unidirectional glass fibre/epoxy.” *Journal of Reinforced Plastics and Composites*, 15 (1), 2-15.
673 Yi, S. and Hilton, H.H. (1998). “Effects of thermo-mechanical properties of composites on
674 viscosity, temperature and degree of cure in thick thermosetting composite laminates during
675 curing process.” *Journal of Composite Materials*, 32 (7), 600-622.
676

677 **List of Tables:**

- 678 Table 1. Summary of the test methods and number of specimens
679 Table 2. Physical properties of the GFRP bars
680 Table 3. Mechanical properties of the GFRP bars before and after conditioning
681 Table 4. Specimen length for the tensile testing of the GFRP bars
682 Table 5. Estimated affected portion of the GFRP bars

683

684 **List of Figures:**

- 685 Figure 1 – Tested GFRP bars specimens
686 Figure 2 - Test setup and instrumentation
687 Figure 3 - Load-deflection and failure behavior of GFRP bars in bending
688 Figure 4 - Load-deflection and failure behavior of the GFRP bars under short-beam shear testing
689 Figure 5 - Stress-strain and failure behavior of the GFRP bars in tension
690 Figure 6 - Relationship of water absorption to the shape ratio and bar diameter
691 Figure 7 - Normalized mechanical properties of the GFRP bars
692 Figure 8 - Property retention of GFRP bars with different diameters
693 Figure 9 - SEM micrographs of the reference GFRP bars
694 Figure 10 - SEM micrographs of the conditioned GFRP bars
695 Figure 11. FTIR spectrum of the GFRP bars before and after conditioning.

696

697 Table 1. Summary of the test methods and number of specimens

Properties	Test Method	No. of Specimens	Reference	Conditioned
Physical properties				
Cross-sectional area (mm ²)	CSA-S806, Annex A (2012)	9	√	--
Fiber content by weight (%)	ASTM D3171-15 (2015)	9	√	--
Transverse CTE, (x10 ⁻⁶ /°C)	ASTM E1131-08 (2014)	9	√	--
Void content (%)	ASTM D5117-09 (2009)	9	√	--
Water absorption at 24 hours (%)	ASTM D570-98 (2010)	15	√	--
Water absorption at saturation (%)	ASTM D570-98 (2010)	15	√	--
Cure ratio (%)	ASTM E 1356-08 (2014)	15	√	--
Tg (°C)	ASTM E 1356-08 (2014)	15	√	--
Mechanical properties				
Flexure	ASTM D4476/D4476M-14 (2014)	6	√	√
Interlaminar shear	ASTM D4475-02 (2016)	6	√	√
Tensile	ASTM D7205/D7205M-06 (2011)	6	√	√

698

699

700 Table 2. Physical properties of the GFRP bars

Property	Bar designation				
	#3	#4	#5	#6	#8
Nominal diameter (mm)	9.5	12.7	15.9	19.1	25.4
Nominal cross-sectional area (mm ²)	70.8	126.6	198.5	286.5	506.7
Actual cross-sectional area by immersion test (mm ²)	83.8 (1.9)	145.0 (1.7)	224.4 (1.2)	317.3 (1.9)	555.7 (5.2)
Fiber content by weight (%)	80.9 (0.2)	81.8 (0.1)	82.6 (0.1)	82.7 (0.2)	83.0 (0.2)
Transverse CTE, (x10 ⁻⁶ /°C)	20.7 (2.3)	20.5 (1.6)	21.5 (1.4)	22.0 (1.8)	21.3 (2.5)
Void content (%)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Water absorption at 24 hours (%)	0.15 (0.01)	0.12 (0.02)	0.10 (0.01)	0.02 (0.00)	0.02 (0.00)
Water absorption at saturation (%)	0.19 (0.01)	0.15 (0.05)	0.14 (0.01)	0.04 (0.01)	0.04 (0.00)
Cure ratio (%)	100 (0)	100 (0)	100 (0)	100 (0)	100 (0)
T_g (°C)	125.8 (1.3)	112.8 (2.5)	109.6 (1.5)	105.2 (1.3)	124.8 (4.9)

701

702

703 Table 3. Mechanical properties of the GFRP bars before and after conditioning

Property	Bar Designation				
	#3	#4	#5	#6	#8
Reference					
Flexural strength, f_u (MPa)	1623.7 (58.2)	1588.1 (93.5)	1757.5 (66.5)	--	1406.3 (151.3)
Interlaminar shear strength, S_u (MPa)	54.7 (1.1)	52.9 (2.1)	55.8 (1.5)	56.0 (0.1)	47.5 (3.7)
Tensile strength, f_t (MPa)	1315.3 (31.1)	1281.5 (35.3)	1237.4 (33.3)	1270.0 (31.4)	1271.0 (29.9)
Tensile modulus, E (GPa)	62.5 (0.4)	61.3 (0.4)	60.0 (1.3)	60.5 (0.5)	61.8 (0.3)
Tensile strain, e	2.3 (0.1)	2.1 (0.1)	2.1 (0.1)	2.1 (0.1)	2.1 (0.1)
Conditioned					
Flexural strength, f_u (MPa)	1440.3 (97.3)	1455.6 (96.4)	1660.0 (62.3)	--	1370.9 (49.9)
Interlaminar shear strength, S_u (MPa)	48.2 (1.5)	50.6 (2.1)	50.2 (2.4)	52.1 (1.8)	47.9 (2.4)
Tensile strength, f_t (MPa)	1251.8 (34.6)	1114.0 (29.4)	1141.1 (41.5)	1095.9 (55.4)	1119.2 (50.0)
Tensile modulus, E (GPa)	63.0 (0.4)	61.9 (0.4)	60.1 (0.2)	60.8 (0.6)	61.7 (0.3)
Tensile strain, e	2.2 (0.1)	1.8 (0.1)	1.9 (0.1)	1.8 (0.1)	1.8 (0.1)

704

705

706 Table 4. Specimen length for the tensile testing of the GFRP bars

Bar Size	Gauge Length (mm)	Anchor Length (mm)	Specimen Length (mm)
#3	465	400	1265
#4	583	510	1603
#5	713	630	1973
#6	848	740	2328
#8	1166	990	3146

707

708 Table 5. Estimated affected portion of the GFRP bars

Affected Portion	#3	#4	#5	#6	#8
Area ($\times 10^{-3}$ mm ²)	138.2	186.2	270.0	111.7	223.0
Thickness ($\times 10^{-3}$ mm)	4.4	4.7	5.4	1.9	2.8
% of the nominal diameter	0.05	0.04	0.03	0.01	0.01

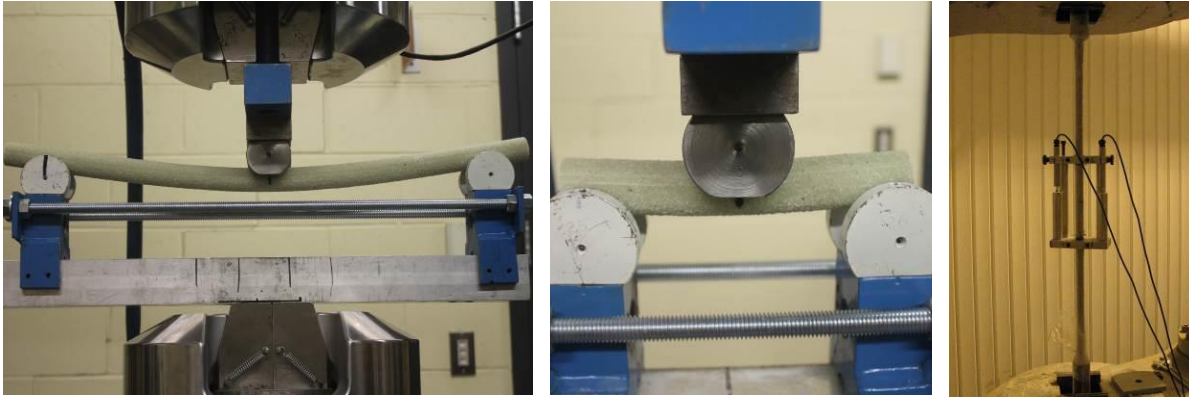
709

710

711
712
713
714
715
716
717
718
719
720
721
722
723
724
725
726
727
728
729
730
731
732
733
734
735
736



Figure 1 – Tested GFRP bars specimens

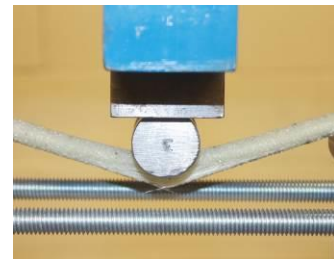
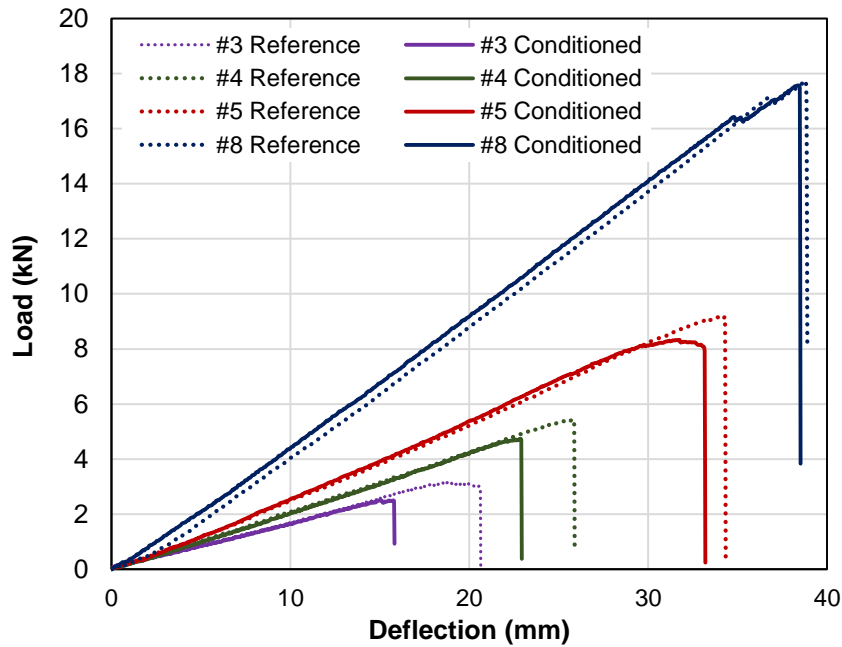


(a) Flexure

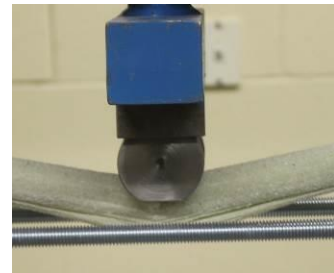
(b) Short-beam shear

(c) Tensile

Figure 2 - Test setup and instrumentation



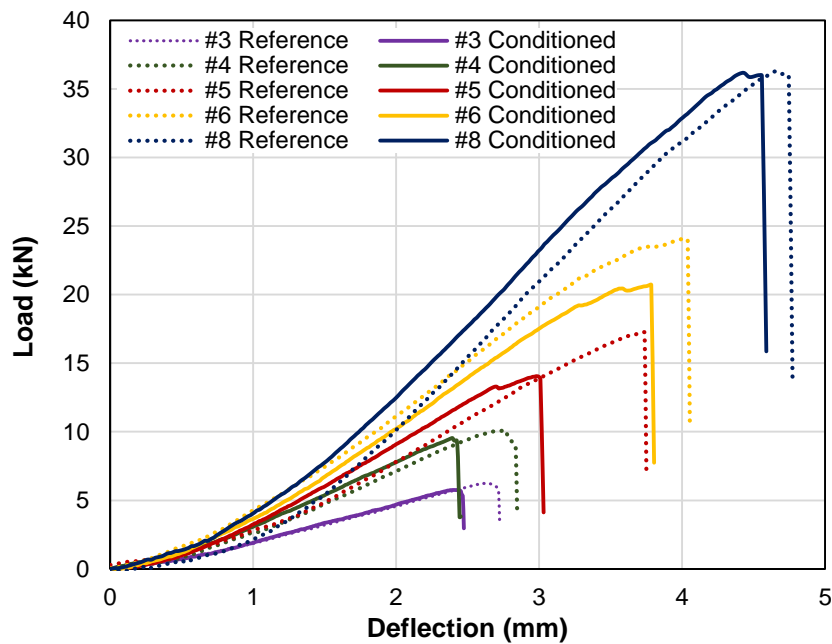
(b) Failure of #3 bars



(c) Failure of #8 bars

(a) Load and deflection behavior

Figure 3 - Load-deflection and failure behavior of GFRP bars in bending



(b) Failure of #3 bars

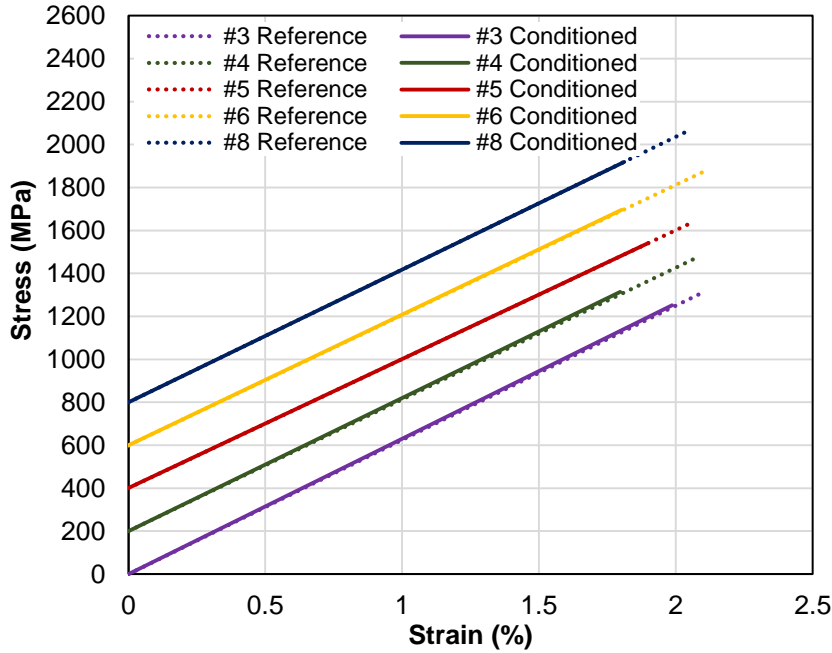


(c) Failure of #8 bars

(a) Load and deflection behavior

Figure 4 - Load-deflection and failure behavior of the GFRP bars under short-beam shear testing

744
745
746
747
748
749
750
751
752
753
754
755
756



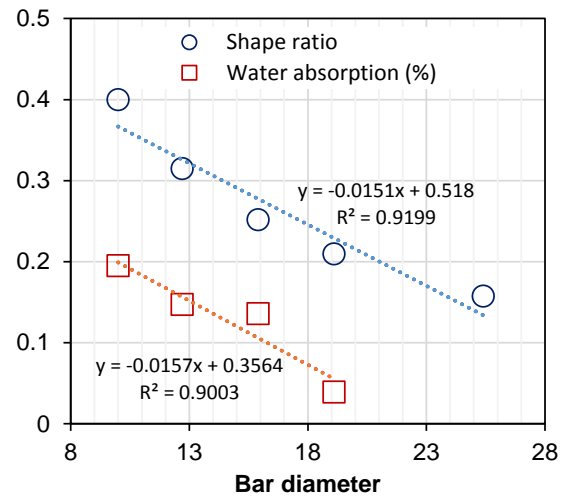
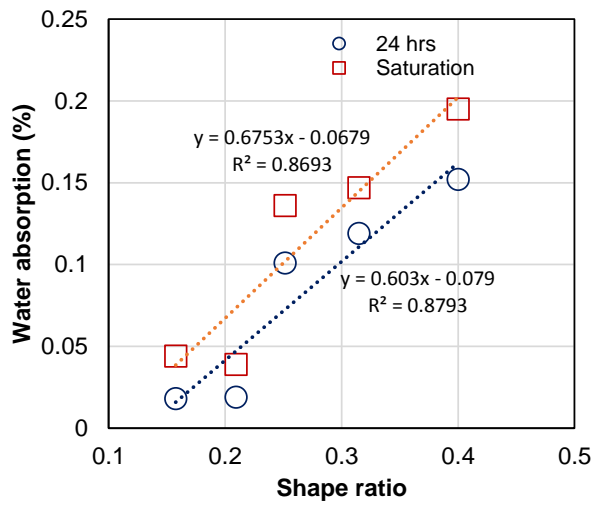
(b) Failure of #3 bars



(c) Failure of #8 bars

(a) Stress and strain behavior

Figure 5 - Stress-strain and failure behavior of the GFRP bars in tension



(a) Water absorption and shape ratio (b) Shape ratio and water absorption with bar diameter

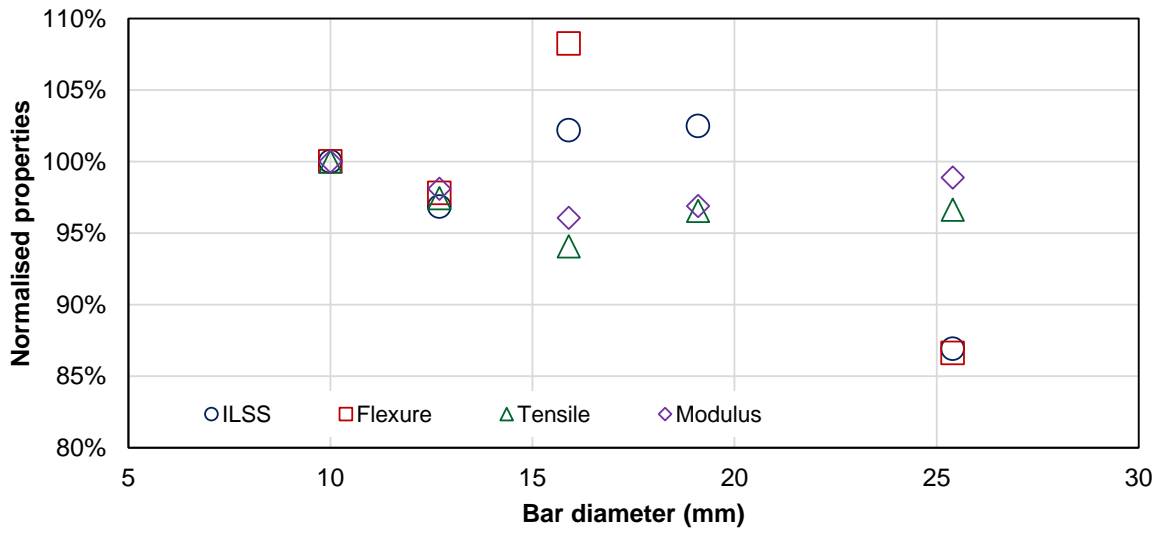
Figure 6 - Relationship of water absorption to the shape ratio and bar diameter

760
761

762

763

764

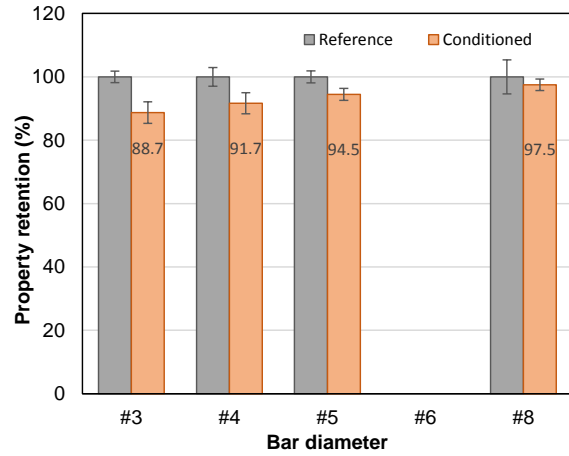
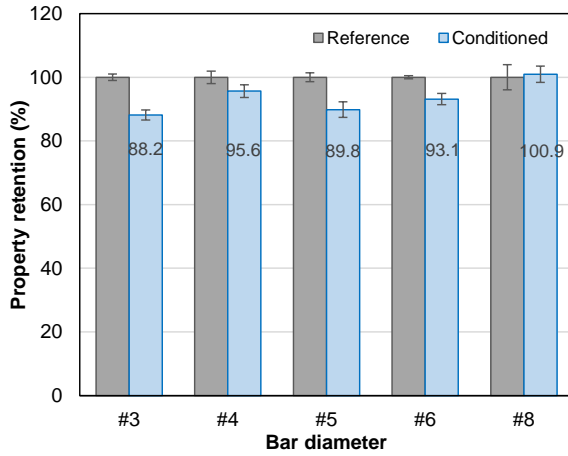


765

766

Figure 7 - Normalized mechanical properties of the GFRP bars

767

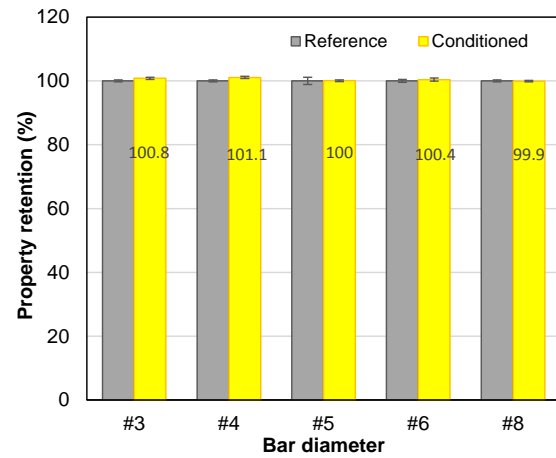
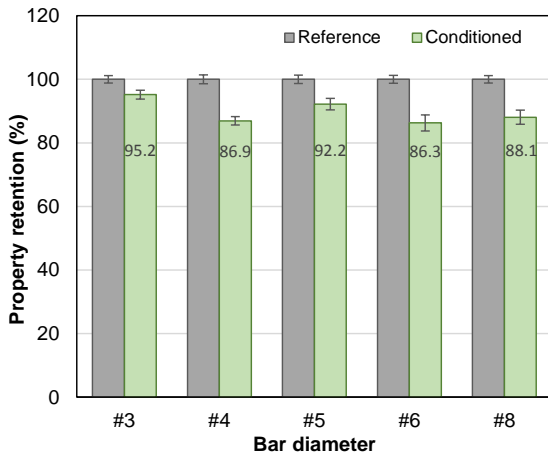


768

769

(a) Interlaminar shear strength

(b) Flexural strength



770

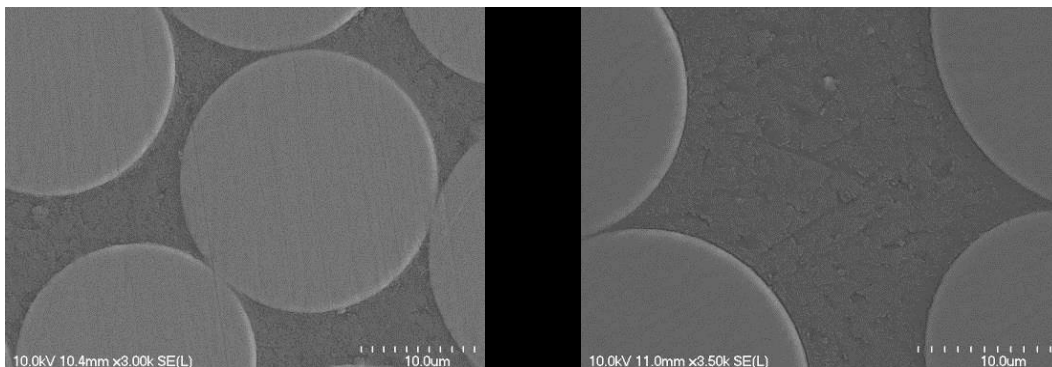
771

(c) Tensile strength

(d) Modulus of elasticity

772

Figure 8 - Property retention of GFRP bars with different diameters



773

774

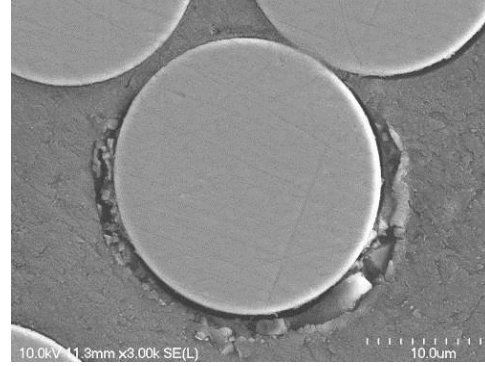
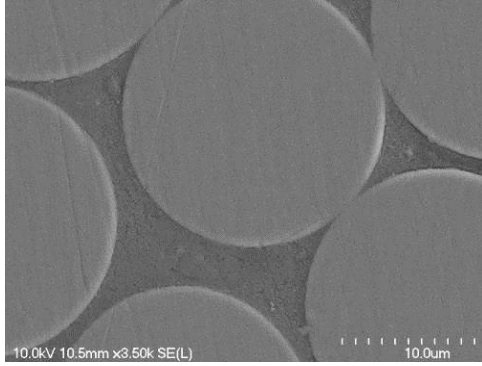
(a) Center of the bar

(b) Near surface of the bar

775

Figure 9 - SEM micrographs of the reference GFRP bars

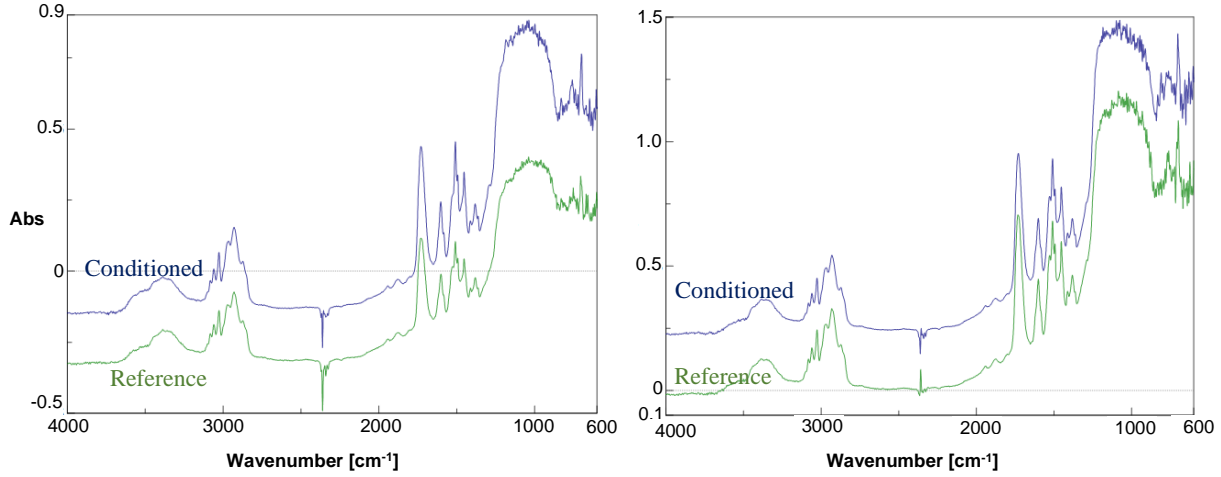
776



(a) Center of the bar

(b) Near surface of the bar

Figure 10 - SEM micrographs of the conditioned GFRP bars



(a) #3 GFRP bars

(b) #8 GFRP bars

Figure 11. FTIR spectrum of the GFRP bars before and after conditioning.