PHYSICAL, MECHANICAL, AND DURABILITY CHARACTERIZATION OF BASALT FRP BARS FOR CONCRETE STRUCTURES

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ABSTRACT: This paper presents preliminary laboratory test results on the physical and mechanical properties of newly developed 16-mm-diameter BFRP bars. Tensile test, transverse and interlaminar shear strength test and bond strength test (pullout test) were conducted on these bars. In addition, the durability performance of the mechanical properties for 1.5 months exposure time at 60^{o}C was addressed. The test results indicated that the physical and mechanical properties fulfill the minimum requirements of CSA S807-10 and ACI 440-2008 to be used as non-prestressed reinforcement. More experimental tests, however, for short and long-term durability issue of the BFRP bars under different environments and exposure conditions are needed.

1 INTRODUCTION

The last two decades, fiber-reinforced polymer (FRP) materials have been successfully applied in the field of civil engineering for reinforcing concrete structures to overcome the corrosion problems and durability issues. FRP materials associated with many advantages over steel reinforcement in term of lightweight, high specific strength and stiffness ratios, non-corrosive materials, neutrality to electrical and magnetic disturbances (Benmokrane et al., 2006; 2007).

Nowadays, basalt FRP (BFRP) is the recent developed FRP composite having the advantages in achieving the goal of enhancing safety and reliability of structural systems compared with the conventional carbon, glass and aramid FRP composites (Wu et al., 2011). Continuous basalt fiber (CBF) is an inorganic fiber, which has many unique excellent performance, such as good mechanical properties, a wide-range of working temperature, acid, salt and alkali resistance, anti-UV, low moisture absorption, good insulation, anti-radiation, and sound wave-transparent properties (Wu et al., 2011). Another important characteristic is represented by the high mechanical behavior comparable to that of glass fibre (Carmignato et al., 2009) that together with the lower cost could make this material suitable to potentially replace glass fibres in various industrial fields like aerospace, civil construction, automotive, energy infrastructure, petrochemical, fire protection, water conservation and hydropower, ocean engineering , transportation and shipbuilding.

2 LABORATORY INVESTIGATION

An extensive research program to develop BFRP composites bars as main reinforcement for concrete structures with optimized mechanical, structural, and durability properties is being in progress at the University of Sherbrooke, Sherbrooke, Qc, Canada. The current study presents a laboratory investigation on the physical and mechanical characteristics of 16 mm diameter BFRP helical ribbed bars, see Fig 1. The physical properties were determined according to the test methods of (ACI 440, 2008) and (CSA S807, 2010). In addition, scanning electronic microscopy (SEM) analysis was performed to examine the porosity and adhesion between the two components of the BFRP bar (resin matrix and fibers). On the other hand, the mechanical properties of the transverse and interlaminate shear, tensile and bond strengths were determined to the appropriate test methods. It should be noted that the mechanical properties were extracted from reference and conditioned specimens' immersion in an alkaline solution at 60oC for 1.5 months to compare their residual shear and tensile strengths to those of the reference specimens.

2.1 Physical Properties

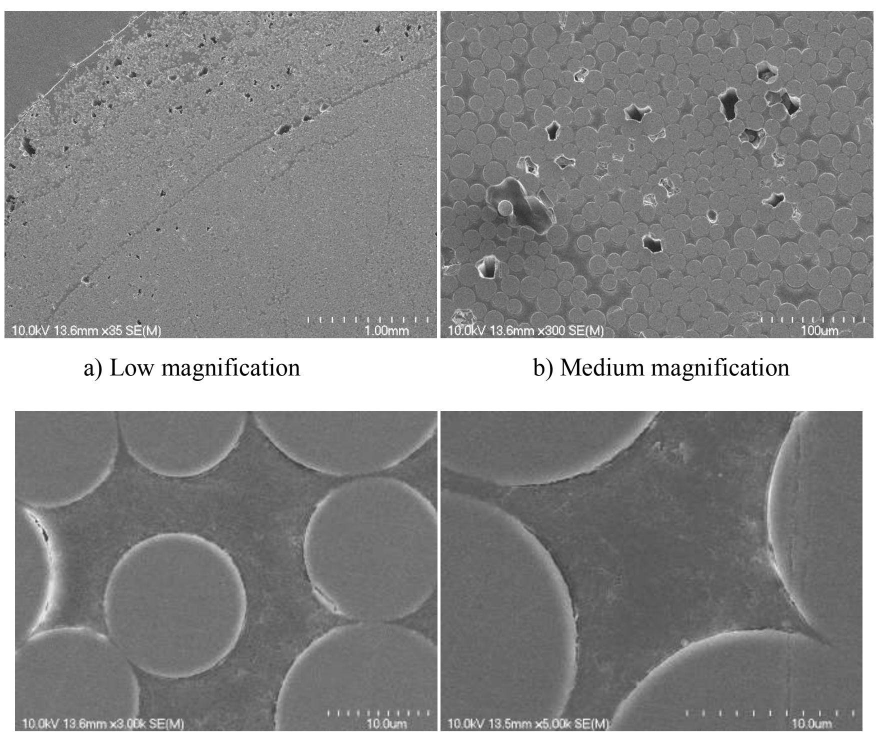
Table 1 lists the different standard test methods were used to determine the physical properties of BFRP bars. The effective of cross-section area was determined according to the (ASTM D7205, 2011) standard and it was an average of 275 mm2. The fiber content by weight of the BFRP bar was 80.5% (an average of three specimens) which is higher than the minimum requirement of the (CSA S807, 2010) and (ACI 440, 2008) (70% fiber content by weight or 55% as fiber content by volume, respectively). The transverse coefficient of thermal expansion (CTE) was performed according to (ASTM E 831, 2012) standard using a TMA apparatus and the transverse (CTE) ranged from 21.9.10-6 to 24.7.10-6 °C-1, with an average of 23.2.10-6 °C-1 while the cure ratio was 98.1% which is satisfied the requirement of the (CSA S807, 2010) (95 %). The glass transition temperature (Tg) was determined according to (ASTM D 3418, 2012) standard. The Tg is an important physical property of the matrix and it is not only an indicator of the thermal stability of the material but also an important indicator of the structure of the polymer and its mechanical properties. The newly developed BFRP bars evidenced a Tg ranging from 111 to 124^{o}C, with a moisture uptake of about 0.02. Table 1 shows the physical characterization test results and compare them against the specified limits of (ACI 440, 2008) and (CSA S807, 2010). The comparison confirms that the tested BFRP bars meet the physical requirements of (ACI 440, 2008) and (CSA S807, 2010).

Figure 1. BFRP bars used in this study.

The porosity and defects, such as de-bonding between fibers and resin, poor fiber distribution, and micro-cracks, are major parameters affecting the long-term durability of the FRP product. Therefore, a scanning electronic microscopy (SEM) analysis was performed to examine the two components of the bars, resin matrix and fibres, and adhesion between them. SEM micrographs of the cross-section of the BFRP bar at different magnifications were presented in Figure 2. The outer section of the material is slightly porous for 1 or 2 mm deep (see Figure 2 (a)) while, the core of the bar is essentially non-porous but includes a few tubular tenths microns of porosity (see Figure 2 (b)). Small gaps at the fiber-resin interface can be observed around some fibers (see Figure 2 (c)). However, these gaps may not have a significant affect on the mechanical properties of the BFRP bar and the mechanical and durability tests are warranty.

2.2 Mechanical Properties

The mechanical characterization included testing of representative reference and conditioned specimens. the conditioned specimens were immersed in an alkaline solution at 60oC for 1.5 months. Transverse shear strength (ASTM D7617, 2011), interlaminar shear (ASTM D4475, 2008), tensile strength properties (CSA S806, 2012- Annex C), and bond strength (ACI 440, 2004, B.3 test method and CSA S806, 2012- Annex G) were conducted to compare the residual strength of conditioned specimens to those of the reference specimens. Figure. 3 shows the different set up configurations for different types of testing.



a) Low magnification

b) Medium magnification

c) High magnification

Figure 2. SEM micrographs of the cross-section of the BFRP 16-mm-diameter at different magnifications

Table 1 Standard test methods and results of physical properties of tested BFRP bars

Property	Standard Test Method	Measured	Specified limit	
		16 mm	ACI 440 (2008)	CSA S807 (2010)
Cross-sectional area (mm^2)	ASTM D7205 – *"Standard Test Method for Tensile Properties of Fiber Reinforced Polymer Matrix Composite Bars"*.	275	N/A	N/A
Fiber content (%)	ASTM D 3171 – "Constituent content of composite", Method I; Procedure G.	80.5 (by wt)	55% (by vol.)	70 (by wt)
Transverse (CTE) ($\times 10^{-6}$ °C^{-1})	ASTM E 831 – "Linear Thermal Expansion of Solids Materials by Thermo-mechanical Analysis (TMA)".	23.2	N/A	40
Density	ASTM D 792 – "Density and Specific Gravity of Plastics by Displacement".	2.09	N/A	N/A
Void content (%)	ASTM D 2734 – "Void Content of Reinforced Plastics"	1	N/A	1
Water absorption at saturation	ASTM D 570 – "Water Absorption of Plastics"	0.20	1	1.0 (D2); 0.75 (D1)
Cure ratio (%)	CSA S807-10, Annex A – "Test Method for determination of Cure Ratio of FRP Bars by DSC".	98.1	N/A	93 (D2); 95 (D1)
(T_g) (^oC)	ASTM D 3418 – "Transition Temperatures of Polymers by Thermal Analysis"	116	100	80 (D2); 100 (D1)

* D1 and D2 classifications elsewhere can be found in (CSA S807, 2010).

2.2.1 Transverse shear strength test

Eight unconditioned and conditioned specimens 200 mm in length were tested using a MTS 810 testing machine equipped with a 500-kN load cell. A displacement-controlled rate of 1.5 mm/min was used during the test, which yielded between 30 and 60 MPa/min until specimen failure. The applied load was recorded during the test using a data acquisition system monitored by a computer. Figure. 3(a) shows the transverse shear test setup and a typical mode of failure for the tested specimens. Table 2 shows the transverse shear strength of the BFRP unconditioned and conditioned specimens. The average transverse shear strength of the unconditioned and conditioned specimens were 251±14.4 and 246±15.4 MPa, respectively, which indicate that the test results were higher than the specified limit according to (CSA S807, 2010) (>160 MPa). Furthermore, the experimental results showed a slight decrease in the transverse shear strength after 1.5 months immersion at 60oC by an average of 1.99%.

2.2.2 Interlaminar shear strength test

BFRP bars were manufactured by a pultrusion process in which fibers were arranged unidirectional and bonded with the polymer matrix. Thus, the in-plane shear stresses were governed by the fiber–matrix interface. Therefore, in-plane shear stresses would be more conducive to inducing interface degradation than transverse shear stresses (Park et al. 2008). The interlaminar shear strength test was conducted according to (ASTM D4475, 2008) on eight specimens. The tests were carried out using a 500-kN MTS 810 testing machine. The specimens were cut to a length of 80 mm while the distance between supports in the test setup was set to four times the nominal diameter of the bar. Figure. 3(b) shows a picture of the test setup and a typical interlaminar shear failure. A displacement controlled rate of 1.3 mm/min was employed during the test. The unconditioned BFRP specimens provided an average interlaminar shear strength of 71 MPa, compared with 68 MPa for conditioned ones. Hence, the conditioned specimens revealed a slight decrease in the interlaminar shear strength by an average of 4.2% compared with the unconditioned specimens. Thus, the interface between the fibers and the resin did not show significant changes after being subjected to alkaline solution for 1.5 months at 60oC.

2.2.3 Tensile strength test

Eight unconditioned and conditioned BFRP bars 16 mm diameter were tested according to standard test method (ASTM D7205, 2011). Each specimen was cut into 1950-mm-long section and anchorage with steel tubes at each end. The anchorage steel tubes were cut to a length of 650-mm and filled cement based grout. The free length (the length between the test specimens between the two anchorages) to bar-diameter ratio was about 40 the bar's diameter (d_b). Each specimen was instrumented with a linear variable differential transformer (LVDT) with a gauge length of 200 mm to capture the elongation during testing. The test was carried out using a 2000-kN Baldwin testing machine and the load was increased until failure. The applied load and bar elongations were recorded using a data acquisition system monitored by a computer. Figure. 3(c) shows a picture of the test setup and a typical mode of failure of the tested specimens. The typical stress-strain curves of the 16-mm-diameter BFRP bars were linear elastic up to failure. For all specimens the mode of failure was brittle failure. Table 3 shows the mechanical properties of test results. The results indicate that the tensile strength of unconditioned and conditioned specimens is 1702 ± 70.0 and 1411 ± 55.0 MPa, respectively. This indicates that the loss of resistance after 1.5 months at 60oC was equal to 17.1%. In addition, the tested BFRP bars evidenced maximum strain at failure ranging from 2.8% to 2.2%, which is higher than the minimum value of 1.2% (CSA S807, 2010).

2.2.4 Pullout bond test

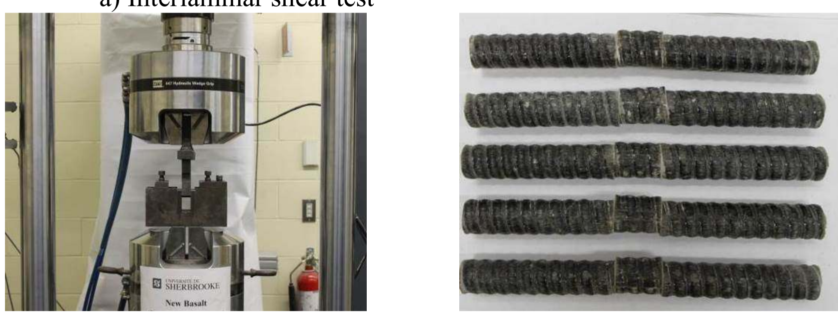
The pullout tests were carried out according to (ACI 440, 2004-B.3 Test Method) and (CSA S806, 2012- Annex G). Five unconditioned specimens were tested under pullout bond test. The embedment length (bond length), namely $5d_b$, was used. The concrete strength has a compressive strength of 35 MPa. Each block had a section of 200 x 200 x 200 mm. The BFRP bars were cut into 1200-mm-long. One end of the bar sample was completely embedded in the concrete block and the other was attached with steel anchorage tube with a length of 400-mm. All the specimens were failed under pure pull-out failure whereas the bar is pulled out from the concrete block without any splitting/cracking in the concrete. As can be seen in Table 3 that the 16-mm-diameter BFRP bars exhibited an average bond stress of 16.8 ± 1.4 MPa, which is higher than the specified limit of (8 MPa) as specified by (CSA S807, 2010).

Table 3 Mechanical Properties of BFRP 16-mm- diameter (Area=201mm2)

Property / Specimens	16-mm-Reference	16-mm-Conditioned (1.5 months)
Transverse shear strength (MPa)	251±14.4	246±15.4
Interlaminar shear (MPa)	71±2.2	68±3.3
Tensile strength (MPa)	1702±70.0	1411±55.0
Tensile modulus of elasticity (GPa)	61±2.5	65±1.8
Ultimate tensile strain (%)	2.8±0.14	2.2±0.05
Bond stress (MPa)*	16.8±1.4	-

* Embedment length equal 80 mm (5 d_b)

a) Interlaminar shear test



b) Transverse shear test

c) Tensile test

Figure. 3: Test setup and typical mode of failure: a) Interlaminar shear test; b) Transverse shear test; c) Tensile test.

3 CONCLUDING REMARKS

This research investigated the physical and mechanical characterization of newly developed 16-mm-diameter BFRP bars. Based on the test results, the following concluding remarks can be drawn:

1. The newly developed BFRP bars 16-mm-diameter fulfill the minimum requirements of (ACI 440, 2008) and (CSA S807, 2010) concerning their physical and mechanical properties to be used as non-prestressed reinforcement for concrete structures.

2. The tested BFRP bars showed no degradation after 1.5 months of accelerated aging in an alkaline solution at 60°C. Strength retentions of 98 and 96% were measured in transverse shear and interlaminar shear strength, respectively.

3. The investigated physical and mechanical characterization on 16-mm-diameter BFRP bars of this study contribute to develop and enhance those newly FRP products, which is a step forward for increasing worldwide interest in utilizing BFRP composites for civil infrastructure applications and to be introduced in design codes.

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