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CHARACTERIZATION OF BASALT AND GLASS FIBER REINFORCED POLYMERS BARS (BFRP AND GFRP)

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Abstract— The superior advancement of composite materials has necessitated the development of different types of fibers that can provide outstanding characteristics at a reasonable cost. A new generation of FRP composites released in the previous decade is Basalt Fiber Reinforced Polymer (BFRP). This research studies the physical and mechanical properties of BFRP bars compared with Glass FRP (GFRP) bars. Variables investigated in this study were the types of fibers (basalt and glass), bar diameter (10 mm and 12 mm), and the fiber volume fraction (50% and 65%). According to the test results, BFRP bars with the same fiber volume fraction as GFRP bars had much improved mechanical properties (approximately 1.28 times those of GFRP bars). Furthermore, the fiber volume fraction has been shown to have a significant influence on the mechanical properties as well as the creep behavior of BFRP bars. Based on the test results, BFRP bars show a promising future as a substitute for GFRP.

Index Terms— Basalt Fiber Reinforced Polymer, Fiber Content, Flexural Strength, Interlaminar Shear, Mechanical Properties, Physical Properties, Tensile Strength.

1 INTRODUCTION

Lately fiber reinforced polymers (FRP) have been utilized as a replacement to conventional steel rebars in the construction sector for decades owing to their high specific strength and stiffness, lightweight and non-corrosive nature [1]. The modulus of elasticity of carbon FRP bars is similar to that of steel and considered to be stiffer than glass FRP. However, the glass FRP bars have earned a considerable portion of manufacturers' attention and long-established availability on market share due to their inexpensive cost, especially in mass applications and their relatively high strength compared to steel [2]. On the other hand, GFRP composites have lower creep rupture stress which was the main reason to limit their spread [3]. The current attempts for producing the FRP composites in the construction sector are dedicated to presenting different and new types of fibers which can give superior properties with a similar cost to generally recognized aramid, glass, and carbon fibers [4]. BFRP composites are considered to be a new generation of FRP composites that have not long ago been presented to the composites industry as a powerful substitute to GFRP composites with similar pricing. Basalt fibers, unlike glass fibers, are made through a single-phase process by fusing basalt rocks with no requirement for auxiliary ingredients [5]. This simplicity of the manufacturing process leads to lower production costs as compared to the conventional type of fibers [6]. In addition, the basalt fibers are considered to be a natural green fiber and environmentally friendly due to energy savings during manufacturing [7].

Predicted to have a wide range of desirable characteristics at a competitive price, BFRP

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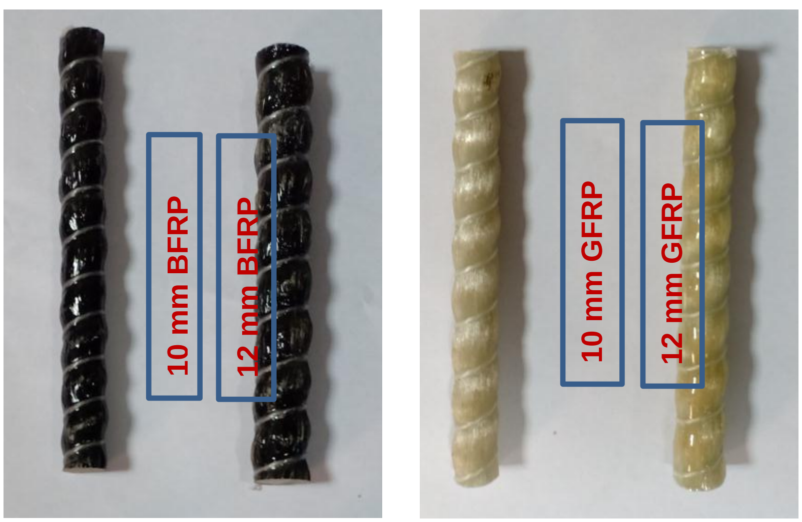
composites show a promising future [8]. However, there are few studies on BFRP characterization available, and BFRP is yet not included in design guidelines and codes. As a result, the physical and mechanical characteristics of BFRP bars will be compared to GFRP bars in this study as a first step toward incorporating BFRP into design guidelines.

2 Experimental Program

As indicated in Fig. 1, this study investigated two different types of FRP bars: BFRP and GFRP bars with nominal diameters of 10 mm and 12 mm. Obtaining the physical properties of the used basalt and glass FRP bars were essential to show any variables that might impact the test findings of the mechanical properties. The FRP bars' physical properties (fiber volume fraction, relative density, and cross-sectional properties, and mechanical properties (tension, flexure, interlaminar shear, and transverse shear) were tested in accordance with ACI Committee 440.3R recommendations [9] and the related ASTM standards [10], [11], [12], [13], [14], [15]. The test matrix is shown in Table 1



BFRP Bars **GFRP Bars**

Fig. 1. Tested basalt and glass FRP bars

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Table 1: Experimental Program Test Matrix for BFRP and GFRP Bars of 10- and 12-mm diameter

General Properties	Specified Property	No. of Specimens	Standards
Physical properties	Cross section properties	5	ACI 440.3R [9]
	Relative density		ASTM D792 [11]
	Fiber content	3	ASTM D3171 [10]
Mechanical properties	Tensile	5	ASTM D7205 [12]
	Flexural		ASTM D4476 [13]
	Interlaminar shear		ASTM D4475 [14]
	Transvers shear		ASTM D7617 [15]

3 Experimental Program

3.1 Fiber Content of FRP Bars

Determining the component content is one of the most important aspects in the characterization of FRP composites since it is utilized in the analytical modeling of composite characteristics and evaluating the quality of the manufacturing process. Furthermore, it is utilized to normalize the mechanical characteristics of the composite material. As per ASTM D3171 [10], four sets were tested for determining the fiber volume fraction: Two GFRP bars with diameters of 10 mm and 12 mm and two BFRP bars with diameters of 10 mm and 12 mm. Five specimens for each FRP bars' type and diameter were cut into 20 mm length and were weighed. Then, they were put in a suitable beaker filled with 50 ml of 70 % nitric acid. The beakers were then heated by putting them on a hot plate for roughly 6 hours until the matrix was entirely digested, as indicated in Fig. 2. The specimens were then cleaned with distilled water and were heated in an oven for one hour at 100° Celsius. In the end, as indicated in Fig. 3, the specimens were weighed again after cooling. The fiber content can be calculated as follows:

$$V_r = \left(M_f / M_i\right) \times 100 \times (\rho_c / \rho_r) \qquad (1)$$

Where V_r is the fiber volume fraction (%), M_f is the final mass of the specimen after digestion (g), M_i is the initial mass of the specimen (g), ρ_c is the density of FRP specimen (g/mm^3), and ρ_r is the density of fibers (g/mm^3).

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Fig. 2. Basalt and Glass FRP tested specimens placed in 70% nitric acid then heated

BFRP 10 mm GFRP 10 mm

BFRP 12 mm GFRP 12 mm

Fig. 3. Remaining basalt and glass fibers after testing

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3.2 Relative Density of BFRP Bars

The relative density of the used FRP bars was assessed in order to establish the degree of material homogeneity and as an additional test for estimating the fiber volume percentage. According to ASTM D792 [11], five specimens from each type and diameter were evaluated by immersing them in water and then measure their weight in the air. The density can be calculated as follows:

Specific gravity = $\frac{a}{a-b}$ (2)

Where a is the apparent mass of specimen (g), and b is the apparent mass of specimen completely immersed in water (g).

Density = Specific gravity × 997.5 (3)

3.3 Cross-Sectional Properties of FRP Bars

The cross-sectional characteristics of FRP bars were tested to determine the consistency and quality of the production process. Five specimens of 200 mm length from each FRP bar type and diameter were cut and evaluated per ACI Committee 440.3R recommendations [9] by precisely measuring their length by taking three different measurements by rotating the specimens 120 degrees each time around their axes and take their average value. Then, their volume was measured by submerging the specimens in water. In the end, the cross-sectional characteristics of the specimens are computed as follows:

a) Cross-sectional Area:

$$A_f = \frac{V}{L_a} \qquad (4)$$

Where A_f is the cross-sectional area of the FRP bars (mm^2), V is the volume of the tested specimen (mm^3), and L_a is the average length of the tested specimen (mm).

b) Equivalent Diameter:

$$d_b = 2\sqrt{\frac{A_f}{\pi}} \qquad (5)$$

Where d_b is the equivalent diameter of the tested specimen (mm).

c) Equivalent Circumference:

$$C_b = d_b * \pi \qquad (6)$$

Where C_b is equivalent circumference of the tested specimen (mm).

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3.4 Tensile Properties of FRP Bars

One of the most significant properties to be considered to differentiate between FRP types is the tensile properties. Thus, it is essential to perform the tensile test to be able to compare the BFRP and the GFRP bars that used in this study. Five specimens of 1000 mm total length and 400 mm free length from each type and diameter were prepared according to ASTM D7205 [12] to be tested in the static tensile test. For the tested FRP bars, steel tubes of 310 mm length, 16 mm internal diameter and 10 mm thickness were used anchorage device when testing the specimens in tension. All specimens were loaded using a universal testing machine of sensitivity 0.5 kN and 100 kN. The steel tubes were cleaned and filled with adhesive material of epoxy base surrounding the FRP bars. To ensure the positioning of the bar inside the steel tubes, hollow rings made from PVC were used. To record the elongation of each specimen, two dial gauges of 40 mm capacity and 0.005 mm sensitivity were attached to the specimens located 200 mm apart. The setup used in the tension test and the typical failure modes are shown in Fig. 4. For the tested FRP bars, the tensile properties are calculated as follows:

a) Tensile Strength:

$$f_u = \frac{T_u}{A} \tag{7}$$

Where f_u is the tensile strength (MPa), T_u is the tension load (N), and A is the cross-section area of the bar (mm^2).

b) Modulus of Elasticity:

$$E_f = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{8}$$

Where E_f is the modulus of elasticity (GPa), $\Delta\sigma$ is the change in tensile stress (MPa), and $\Delta\varepsilon$ is the change in the tensile strain.

c) Ultimate Tensile Strain:

$$\varepsilon_u = \frac{L_i - L_o}{L_o} \tag{9}$$

Where ε_u is the ultimate tensile strain, L_i is the gauge length after loading (mm), and L_o is the initial gage length (mm).

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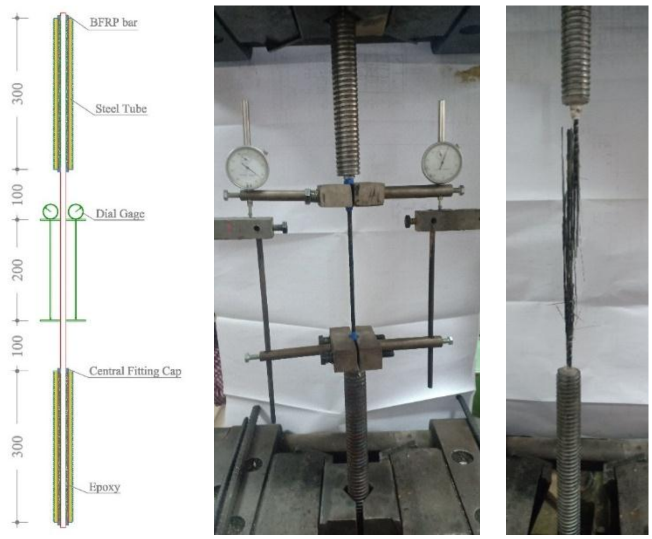

Fig. 4. Tension test setup and typical failure mode

3.5 Flexural Strength of FRP Bars

Assessment of the flexure strength of the used FRP bars was included in this study to expand the comparison between the BFRP and GFRP bars. For each FRP bar type and diameter, five specimens of length 20 times the bars' diameter were tested following the ASTM D4476 [13] using a three-point loading test till failure, as shown in Fig. 5. The span between the supports was selected to be 18 times the bar diameter. A universal testing machine of a capacity of 50 kN was used in this test. As estimated, all the tested specimens failed due to the outer fibers tensile fracture in the tension side. For the tested FRP bars, the flexural strength can be calculated as follows:

$$S_f = \frac{P_f L_f C}{4I} \qquad (10)$$

Where S_f is the flexural stress in outer fibers at midspan (MPa), P_f is the flexural load (N), L_f is the support span (mm), C is the distance from the centroid to extremities (mm), and I is the moment of inertia (mm^4).

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Test Setup

BFRP bars of 10 mm diameter

BFRP bars of 12 mm diameter

GFRP bars of 10 mm diameter

GFRP bars of 12 mm diameter

Fig. 5. Flexural test setup and typical failure mode

3.6 Interlaminar Shear Strength of FRP Bars

Due to the manufacturing process using pultrusion, horizontal stress happens between the resin matrix and the unidirectional fibers in the FRP bars, this leads to a higher deterioration than that induced due to transverse shear stresses [16]. Thus, using the short beam test procedure, the interlaminar shear strength (apparent horizontal shear strength) was assessed for the used FRP bars following ASTM D4475 [14]. Five specimens of length 5 times the bar diameters were used for each bar type and diameter were tested in a bending configuration using a span of three times the bar diameter. The tested specimens were loaded till failure as presented in Fig. 6. For the tested specimens, the interlaminar shear strength can be calculated as follows:

$$S = 0.849\frac{P_{is}}{d^2} \qquad (11)$$

Where S is the interlaminar shear strength (MPa), P_{is} is the interlaminar shear ultimate load (N), and d is the specimen diameter (mm).

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Test Setup

BFRP bars of 10 mm diameter

BFRP bars of 12 mm diameter

GFRP bars of 10 mm diameter

GFRP bars of 12 mm diameter

Fig. 6. Short beam test setup and typical failure mode.

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3.7 Transverse Shear Strength of FRP Bars

For each bar type and diameter, five specimens of 200 mm length were properly cut and put into a double shear device with a sharp cutting blade, according to ASTM D7617 [15]. The device was fitted in a 50 kN capacity universal testing machine and loaded till failure, as presented in Fig. 7. For the tested specimens, the transverse shear strength is calculated as follows:

$$\tau_u = \frac{P_s}{2A} \qquad (12)$$

Where τ_u is the ultimate tensile load (N) and P_s is the maximum shear force (N).

Test Setup

BFRP bars of 10 mm diameter

BFRP bars of 12 mm diameter

GFRP bars of 10 mm diameter

GFRP bars of 12 mm diameter

Fig. 7. Short beam test setup and typical failure mode.

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4 Results and Discussion

4.1 Physical Properties

As part of the characterization of the materials, the physical properties were evaluated to discover any variables that were not taken into consideration in this research. Based on prior tests' results, the physical characteristics were assessed and computed. The results are shown in Table 2. Based on the previously indicated test findings, BFRP and GFRP bars exhibited a fair standard deviation that indicating excellent consistency and quality of the production process. Furthermore, the test results showed that the fiber volume fraction of the used BFRP (diameter 10 mm and 12 mm) and GFRP bars (diameter 10 mm and 12 mm) is 50% and 65%, respectively. This difference has been significantly affected on the mechanical characteristics of the tested bars.

Table 2: Physical Properties of FRP Bars

Property	BFRP		GFRP	
Nominal diameter (mm)	10	12	10	12
Cross-sectional area (mm^2)	80.46±1.36	112.32±1.10	80.38±1.52	114.46±1.37
Equivalent diameter (mm)	10.12±0.09	11.96±0.06	10.12±0.10	12.07±0.07
Equivalent circumference (mm)	31.80±0.27	37.57±0.18	31.78±0.30	37.92±0.23
Density (kg/m^3)	1845.4±29.1	1813.5±22.8	1901.2±30.4	1911.2±20.7
Fiber volume fraction (%)	50.65±2.30	50.42±0.78	65.34±0.73	65.24±1.12

4.2 Mechanical Properties

Based on the aforementioned test procedures, the BFRP and GFRP bars were tested, and the short-term mechanical characteristics were evaluated. The test results are shown in Table 3 and Fig. 8 to Fig. 10. The results of the tests revealed that the BFRP bars of 10 and 12 mm diameter showed minor improved mechanical characteristics compared with their corresponding GFRP bars. However, in comparison with those of GFRP bars, the less fiber volume fraction of BFRP bars with a diameter of 10 mm and 12 mm proves the superiority of the mechanical characteristic

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of the BFRP bars. The test findings have shown that, in addition to the ease of the production process and being environmentally friendly, BFRP bars offer superior mechanical characteristics when compared with GFRP bars with the same fiber volume fraction at a competitive price. All these benefits give BFRP bars the edge in the construction sector and strengthening procedures over GFRP bars.

Table 3: Mechanical Properties of FRP Bars*

Property	BFRP		GFRP	
Nominal diameter (mm)	10	12	10	12
Tensile strength (MPa)	986.70±11.7	1022.32±3.0	955.68±2.0	1081.60±2.2
Normalized tensile strength** (MPa)	1948.08	2027.61	1462.63	1657.88
Modulus of elasticity (GPa)	39.77±0.88	45.66±1.45	39.45±0.28	46.57±0.52
Ultimate strain (%)	2.52±0.05	2.27±0.05	2.43±0.03	2.31±0.0.
Flexural strength (MPa)	1310.5±67	1315.9±46	1227.5±56	1231.3±42
Transverse shear strength (MPa)	148.46±3.26	148.54±2.00	147.19±3.16	148.37±2.86
Interlaminar shear strength (MPa)	55.19±3.71	56.31±1.72	56.37±1.60	57.84±0.70

* *The mechanical properties were calculated based on the nominal diameter.

** Normalized Tensile strength = Tensile strength/Fiber volume fraction.

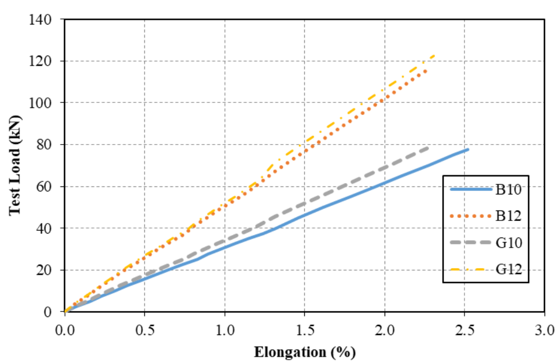

Fig. 8. Load versus percentage of elongation for all specimens

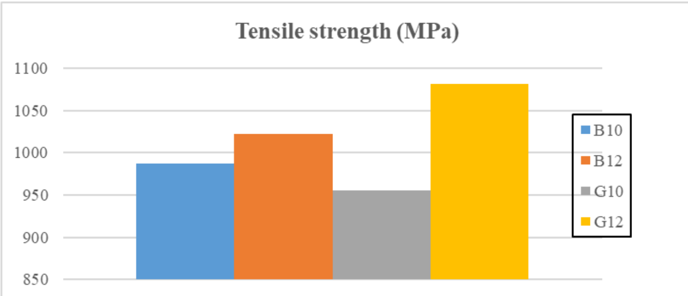

Fig. 9. Tensile strength (MPa) for tested FRP bars

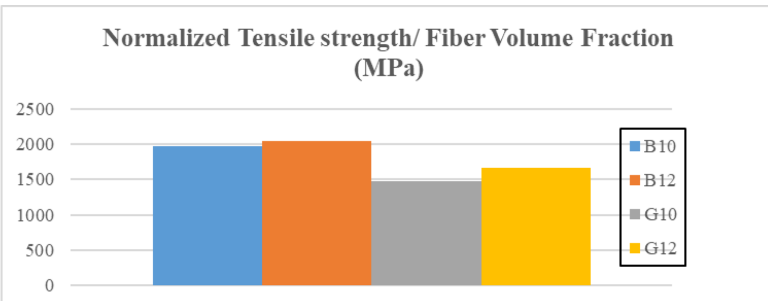

Fig. 10. Normalized Tensile strength (MPa) for tested FRP bars

4.3 Effect of FRP Bar Type

As discussed in the mechanical properties of the tested FRP bars, the basalt FRP bars of the same diameter and fiber volume fraction can have 1.28 times the tensile strength when compared to the GFRP bars. Thus, they are considered to be superior and preferable in strengthening processes. Knowing that both types of the FRP bars, BFRP and GFRP bars, have nearly the same cost and taking into account the BFRP bars manufacturing process is considered to be eco-friendly and need less energy, this makes the BFRP bars a good substitute to the more common GFRP bars.

5 Conclusions

This research shows a comparative study between the BFRP and GFRP bars taking into consideration the physical and mechanical characteristics of the tested bars. The factors evaluated in this study were fiber type, fiber volume fraction, and bar diameter. The following findings can be derived based on the test results:

- The BFRP bars, of the same fiber volume fraction as GFRP bars, have greater

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mechanical characteristics of about 1.28 times the GFRP bars with approximately the same cost.

- The fiber volume fraction of the FRP bars plays a great role and has a significant influence on the mechanical characteristics of bars.

- The BFRP bars are considered to be a great substitute for the GFRP bars taking into consideration the superiority in the mechanical properties, the lower energy demand during manufacturing, and being eco-friendly.

- The physical characteristic of the FRP bars has to be taken into consideration as it affects the behavior of the bars when used in the construction sector or as strengthening elements.

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