Construction and Building Materials 114 (2016) 383–391

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effects of basalt and glass chopped fibers addition on fracture energy and mechanical properties of ordinary concrete: CMOD measurement

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HIGHLIGHTS

- Chopped basalt and glass fibers with 24 mm lengths were used for producing of concrete specimens.
- Four different fiber contents (0.5, 1, 2 and 3 kg/m^3) were selected for basalt and glass fiber reinforced concrete.
- Fracture energy and mechanical properties of basalt and glass fiber reinforced concrete were evaluated.
- Microstructures of the fiber reinforced concrete were investigated.

ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form 23 March 2016
Accepted 29 March 2016
Available online 4 April 2016

Keywords:
Basalt fiber
Glass fiber
Fracture energy
CMOD
Mechanical properties
Microstructure

ABSTRACT

This study investigates fracture behavior of basalt fiber reinforced concrete (BFRC) and glass fiber reinforced concrete (GFRC) comparatively. For this purpose, three-point bending tests were carried out on notched beams produced using BFRC and GFRC with 0.5, 1, 2 and 3 kg/m^3 fiber contents to determine the value of fracture energy. Fracture energies of the notched beam specimens were calculated by analyzing load versus crack mouth opining displacement (CMOD) curves by the help of RILEM proposal. In addition, microstructural analysis of the three components; cement paste, aggregate, basalt and glass fiber were performed based on the Scanning Electron Microscopy and Energy-Dispersive X-ray Spectroscopy examinations and analysis were discussed. The results showed that the effects of the fiber contents on fracture energy were very significant. The splitting tensile and flexural strength of BFRC and GFRC were improved with increasing fiber content whereas a slight drop in flexural strength was observed for high volume of fiber content. On the other hand, effect of fiber addition on the compressive strength and modulus of elasticity of the mixtures was insignificant.

1. Introduction

Concrete is a composite material with high compressive strength, low tensile strength and strain capacity. Fibers have been used to improve flexural strength, toughness, load carrying, impact, fatigue and abrasion resistance, deformation capability and ductility characteristics of concrete. In addition, fibers control the crack patterns and determine failure modes of concrete members [1–4]. There are many fibers utilized in cement and concrete materials. The most common fibers are glass, carbon, aramid, polypropylene, and basalt fibers. Fibers have remarkable structural perfection, thanks to their limited dimensions [5,6].

Basalt is a rock having high strength and durability [5,7]. Basalt fibers (BF) are made out of basalt rocks after melting procedure. Diameter range of BFs is between 13 and 20 µm. Also, BFs heat protection, thermal resistance, acoustic insulation and durability [1,5,8]. Even if BFs have aforementioned advantages, studies about BFs are limited [2,9,10]. Therefore further experimental studies should be carried out to determine effects of BF on physical and mechanical properties of composites.

Fracture energy of concrete is a substantial property used in design of concrete structures. Fictitious Crack Model (FCM) proposed by Hillerborg [11,12] is commonly used fracture mechanics model for analysis. Fracture energy (G_f) is the energy needed to develop one crack completely. RILEM [13] and Peterson [14] recommended a method for calculation of G_f using three-point bending test on notched beams.

One of the major roles of fibers in concrete is to increase the fracture energy [15–17]. Even if many fiber types have been used in concrete [15,17–19], knowledge related to mechanical properties, fracture behavior and microstructure of basalt fiber reinforced concrete (BFRC) is insufficient. Therefore, the main objectives of

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http://dx.doi.org/10.1016/j.conbuildmat.2016.03.176
0950-0618/

this study are to determine mechanical properties, fracture behavior and to investigate microstructure of BFRC and glass fiber reinforced concrete (GFRC), comparatively. To determine the value of fracture energy, three-point bending tests were performed on notched beams produced using GFRC and BFRC with 24 mm fiber length and 0.5, 1, 2 and 3 kg/m^3 fiber contents.

2. Experimental study

2.1. Materials and specimen preparation

In this study, CEM I 42.5R Portland cement was used for producing of BFRC and GFRC specimens. The mixture proportions of the concretes are shown in Table 1. The W/C ratio was kept constant as 0.50 for all mixtures. Also, 1.0% high-range water reducing admixture was used by weight of cement for concrete mixtures to achieve proper workability.

In order to determine the fracture energies of Ref, BFRC and GFRCs, 27 notched beams were tested by three point bending test. The dimensions of all specimens are 50 × 100 × 480 mm with a notch height to beam height ratio (a_0/d) equal to 0.3 and a free span to beam height ratio (S/d) equal to 4 in accordance with RILEM [13]. Details of the notched beam specimen are given in Fig. 1.

As it was mentioned above, BFs and GFs with 24 mm fiber length and four different (0.5, 1, 2 and 3 kg/m^3) fiber contents were used to reveal effects on mechanical and fractural behavior of BFRCs and GFRCs. Detailed properties provided by manufacturer and BFs and GFs are presented in Table 2 and Fig. 2 [5,6]. Modular steel molds having a plate in the middle to form notches have been used for producing of the notched beam specimens (Fig. 3).

2.2. Methods

Compressive strength tests have been carried out on three 150 mm × 300 mm cylinder specimens and averages of the test results of each series were obtained. Splitting tensile strengths of 150 mm cube specimens were calculated using the following expression:

$$f_{st} = 2P/\pi a^2 \tag{1}$$

where P and a are the ultimate load and edge dimensions of the specimen, respectively. Test specimens were loaded linearly as displacement controlled using Universal Test Machine (Fig. 4). Time versus Crack Mouth Opening Displacement (CMOD) relation is given in Fig. 5. As seen in the figure displacement controlled loading is almost linear. Loading speed of the three-point bending test was determined as 0.009 mm/min (Fig. 5). For all the specimens end of test were determined as 95% drop in peak load.

CMOD was measured using a clip gauge located in mid-span of the beam by the help of steel knife edges. A video-extensometer was used to measure the deflection of the middle span. Fracture energy (G_f) was calculated by the help of the RILEM [13] proposal given in Eq. (2).

$$G_f = \frac{W_0 + mg\delta}{A} \tag{2}$$

where W_0 is the area under the load-CMOD curve (N/m), mg is the self-weight of the specimen between supports (kg), δ is the maximum displacement (m), and A is the fracture area [b(d − a_0)] (m^2); b and d are the width and height of the beam, respectively. Flexural strength of concretes was calculated using three-point bending test results with Eq. (3).

$$f = \frac{3PS}{2b(d - a_0)^2} \tag{3}$$

where P is the maximum load, S is the span length, b is width of the specimen, d is height of the specimen, and a_0 is notch depth. Modulus of elasticity (E) of the BFRC and GFRC are calculated from the measured initial compliance C_i of load-CMOD curve using Eq. (4) [20–23].

$$E = \frac{6Sa_0V_1(\alpha)}{(C_i bd^2)} \tag{4}$$

where $V_1(\alpha)$ is a function (Eq. (5)) dependent on $(\alpha = (a_0 + h_0)/(d + h_0))$ and h_0 thickness of steel knife edge,

$$V_1(\alpha) = 0.76 - 2.38\alpha + 3.87\alpha^2 - 2.04\alpha^3 + 0.66/(1-\alpha)^2 \tag{5}$$

Table 1
Mixture proportion of the concretes.

Concrete code	Fiber Content (kg/m^3)	Cement (kg/m^3)	W/C ratio	Coarse aggregate (5-12 mm) (kg/m^3)	Fine aggregate (0–5 mm) (kg/m^3)	Super plasticizer (kg/m^3)
Ref	–	350	0.5	740	1100	3.5
BFRC-24-0.5	0.5					
BFRC-24-1	1					
BFRC-24-2	2					
BFRC-24-3	3					
GFRC-24-0.5	0.5					
GFRC-24-1	1					
GFRC-24-2	2					
GFRC-24-3	3					

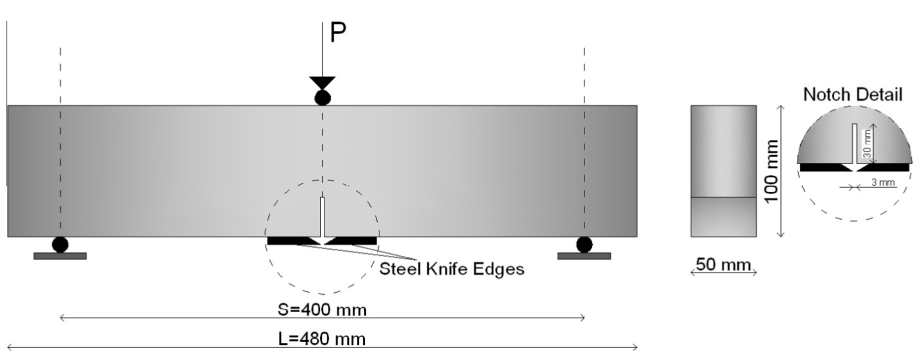


Fig. 1. Dimensions and details of notched beam test specimens.

Table 2
Properties of basalt and glass fiber.

Fiber type	Fiber length (mm)	Diameter (μm)	Modulus of elasticity (GPa)	Elongation (%)	Tensile strength (MPa)	Density (g/cm^3)
Basalt	24	13–20	88	3.15	4000–4500	2.80
Glass	24	10–17	76	2.65	3000–3600	2.60

Fig. 2. Basalt and glass fibers with 24 mm length.

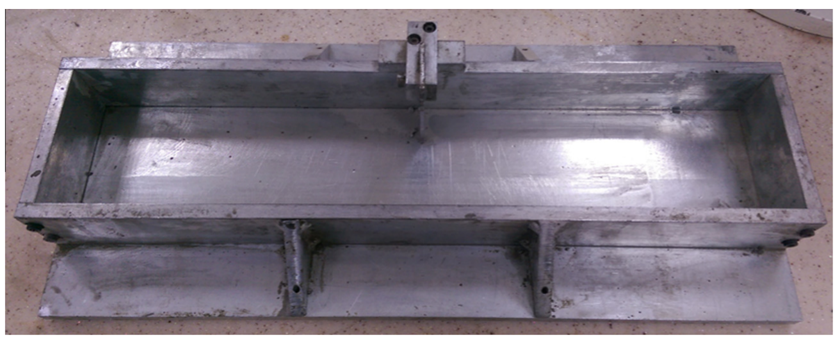


Fig. 3. Steel mold used for producing of notched beam test specimens.

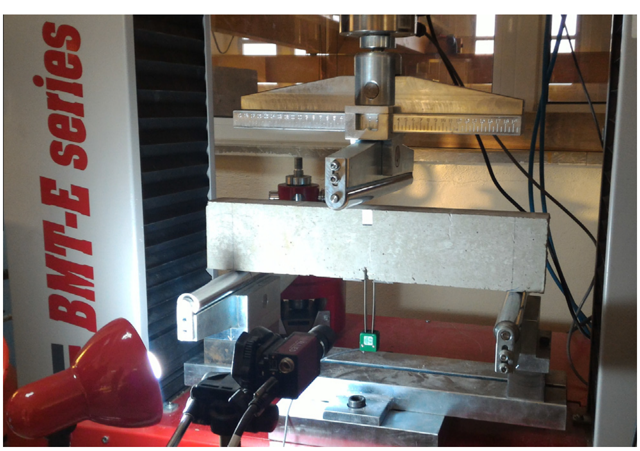


Fig. 4. Three-point bending test set-up.

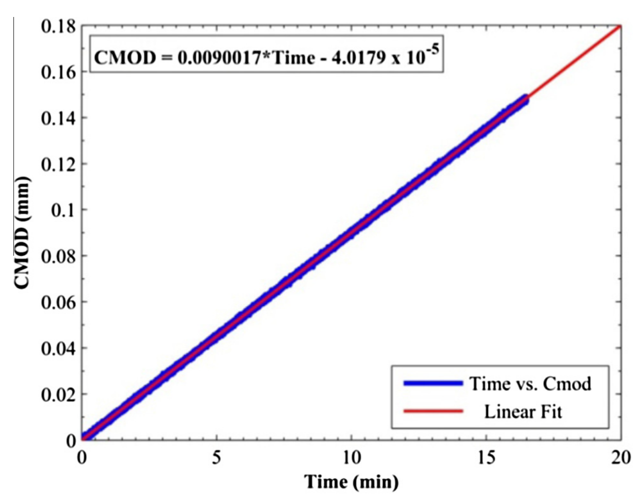


Fig. 5. Time-CMOD relation of three-point bending test.

3. Results and discussion

3.1. Compressive strength

Average compressive strengths of Ref, BFRC and GFRC obtained from cylinder specimens are given in Fig. 6. It is seen in the figure, there is no significant effect of different fiber types (Basalt and Glass) and fiber contents (0.5, 1, 2 and 3 kg/m^3) on compressive strength. However, compressive strength increased for all specimens compared to Ref except for GFRC-24-3 mixture. Maximum 7% increase occurred in BFRC-24-3 with respect to Ref specimen.

3.2. Splitting tensile and flexural strength

Splitting tensile strengths of the mixtures are given in Fig. 7. In some studies [6,20], it has been reported that splitting tensile test

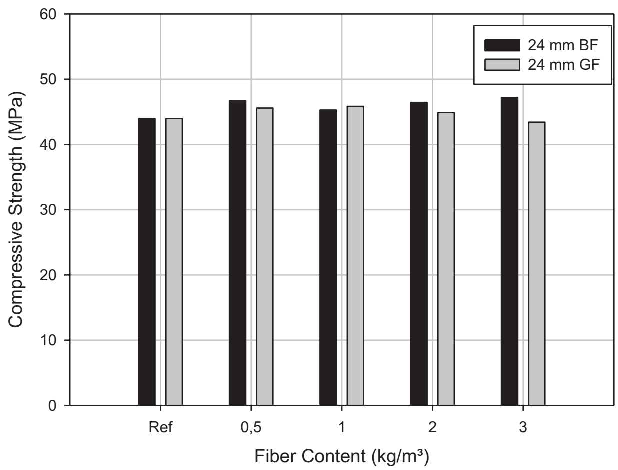


Fig. 6. Compressive strengths of the mixtures.

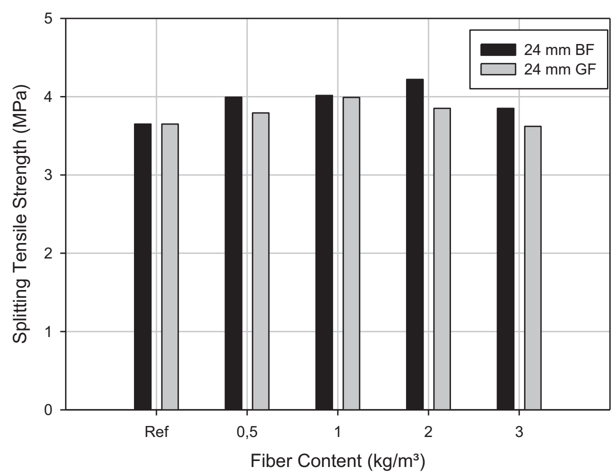


Fig. 7. Splitting tensile strengths of the mixtures.

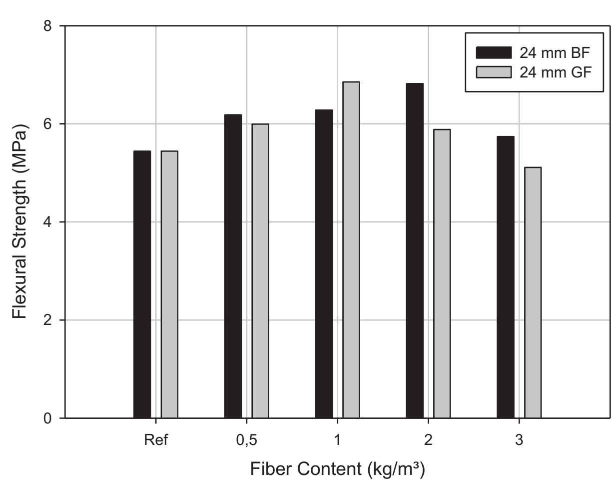


Fig. 8. Flexural strengths of the mixtures.

is not convenient test to determine direct tensile strength that existence of mixed stress areas and different fiber distribution. It has also expressed that it gives idea about the ductility of the material. In this study, it was obtained from the test, BRFC and GFRC specimens did not separate out after first cracking unlike Ref specimen. This result shows that BF and GFs enhance ductility of Ref exhibiting brittle behavior. In addition BFs and GFs increased the splitting tensile strength of the mixtures but for GFRC-24-3. Maximum increase (10%) occurred in BFRC-24-2 compared to Ref specimen. However, the increase in splitting tensile strength began to decrease for BFRC-24-3 and GFRC-24-2 specimens.

Flexural strength values of BFRC, GFRC and Ref test specimens were calculated by Eq. (3) using the results obtained from three-point bending test are given in Fig. 8. It is clearly seen from the figure, addition of BFs and GFs considerably increased flexural strengths of the mixtures with respect to Ref specimen except for GFRC-24-3 notched beam specimen. Increases in flexural strengths are more apparent for GFRC-24-1 and BFRC-24-2 concrete mixtures. Highest flexural strengths occurred for BFRC and GFRC mixtures were 6.85 MPa and 6.82 MPa, respectively. Decrease in flexural strength more distinctive for GFRC-24-2 (5.88 MPa), GFRC-24-3 (5.11 MPa) and BFRC-3 (5.74 MPa) test specimens.

3.3. Fracture energy and modulus of elasticity

Load-CMOD curves of three-point bending test of notched beam specimens are given in Fig. 9. In the figure, it was aimed by drawing Load-CMOD curves separately to demonstrate fiber type and content on load carrying capacity and CMOD more clearly. In addition, all the results of load-CMOD curves were given collectively to make relative comparison between fiber type and fiber contents. It is apparent from Fig. 9 that GFRC-24-1 and BFRC-24-2 have the highest and almost the same load carrying capacity. For all the contents of BF and GF reached peak loads were higher than those of Ref beam test specimen, except for GFRC-24-3.

G_f of BFRC, GFRC and Ref notched beam specimens with different fiber type and content were calculated by using area under the load-CMOD curves (W_0) according to Eq. (2). Changing of W_0 corresponding to CMOD and calculated G_f of the test specimens are illustrated in Fig. 10 and Fig. 11, respectively.

It can be seen from Fig. 11 that addition of BFs and GFs considerable increased the G_f of test specimens compared to Ref test specimen. As it was expected, a slight drop in fracture energies were started after GFRC-24-1 and BFRC-24-2 test specimens. The highest G_f was obtained for GFRC-24-1 (96.06 N/mm) and BFRC-24-2 (87.79 N/mm) test specimens. These values are almost 35% higher than those of Ref notched beam specimens. This result indicates that BFs and GFs increase ductility and energy dissipation capacity of plane concrete.

Modulus of elasticity values of the notched beam specimens were determined by the help of Eq. (4) using the results of three-point bending test and given in Fig. 12. Modulus of elasticity values are around 31,500–37,300 MPa and the highest value was obtained in BF-24-3 test specimen. These values are parallel to the compressive strength results. Decreases in modulus of elasticity are more apparent for GFRC concrete mixtures.

Mechanical properties and fracture energy values obtained from cube, cylinder and notched beam specimens are given in Table 3.

3.4. Microstructural analysis

Microstructural analysis of the three components for BFRC and GFRC concrete mixtures; cement paste, aggregate and fiber (basalt and glass) were performed based on the Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) examinations. Fig. 13 shows the SEM image (1000×) of the BFRC-24-2 and GFRC-24-2 test specimen. It is clearly seen from Fig. 13a; BF has been partly coated with cement paste although it has smooth surfaces. Even if it is not possible to mention about perfect bonding because of the slippage of BF from cement paste,

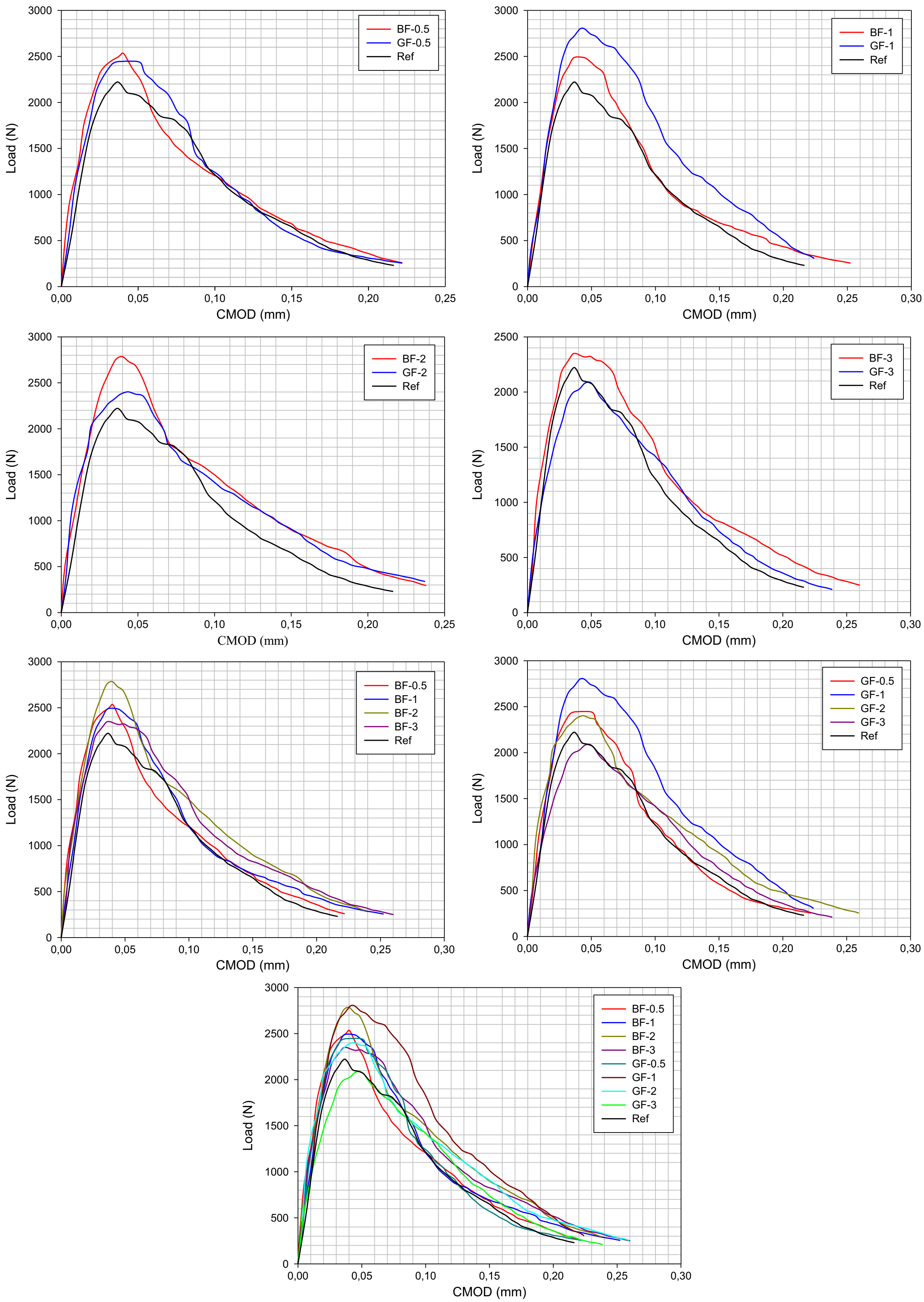


Fig. 9. Load-CMOD responses of three-point bending tests.

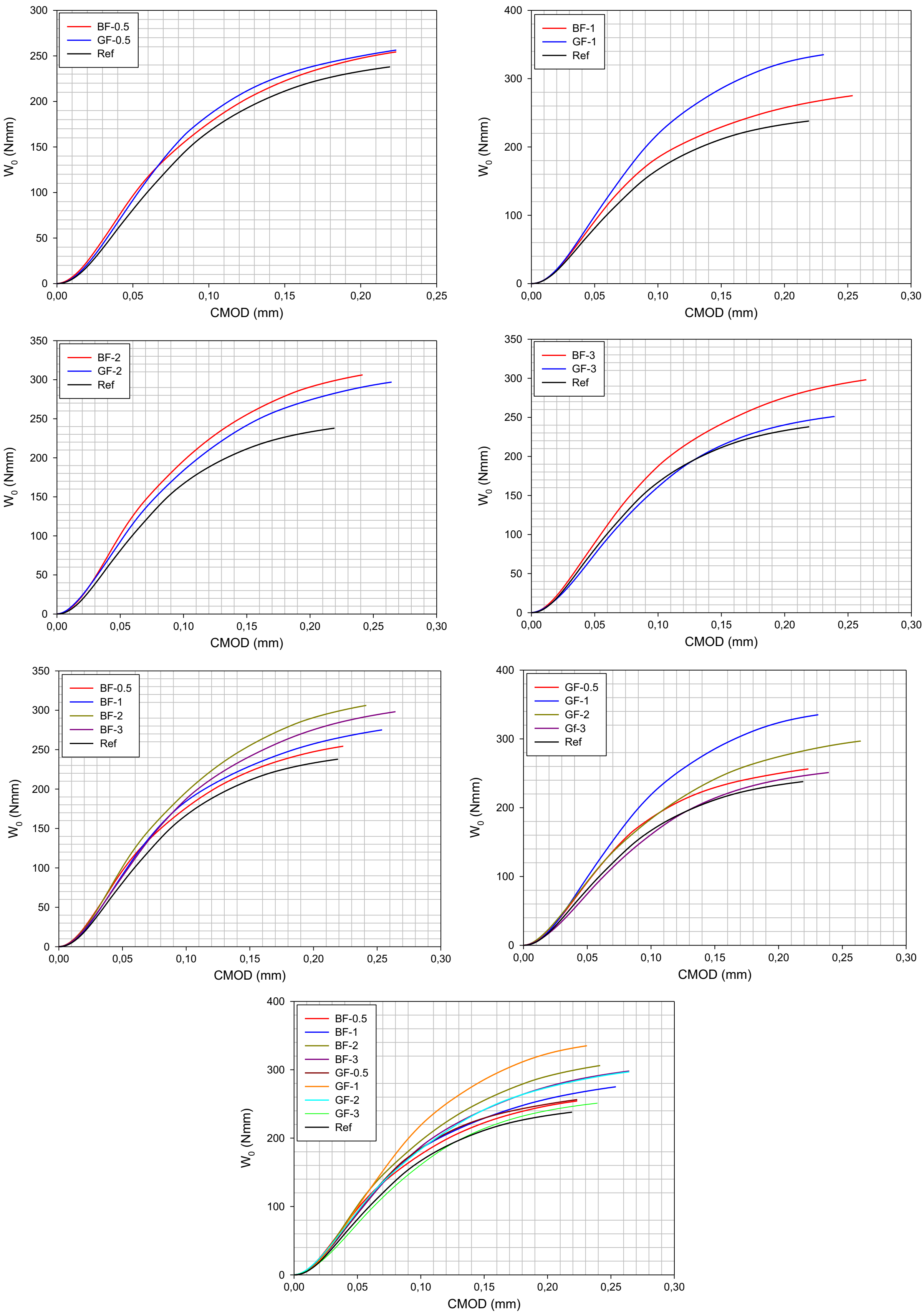


Fig. 10. Changing of W_0 corresponding to CMOD.

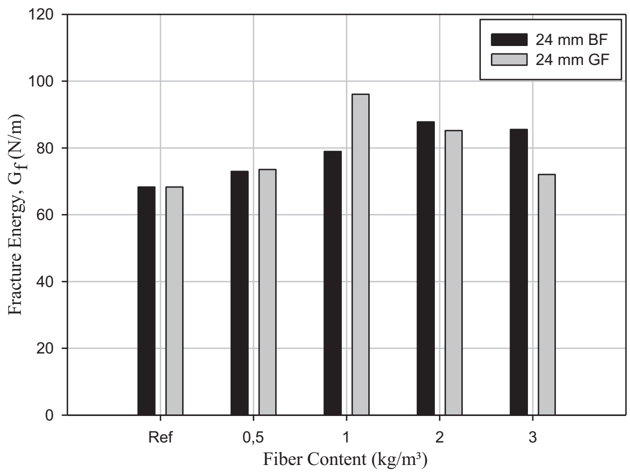


Fig. 11. Fracture energies of notched beam specimens.

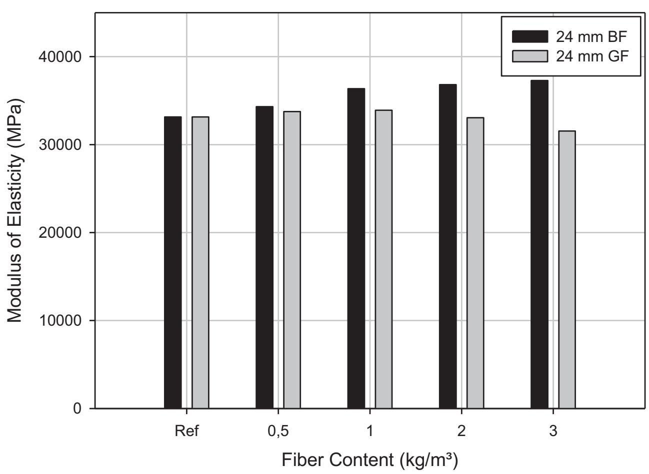


Fig. 12. Modulus of elasticity values calculated using three-point bending test results.

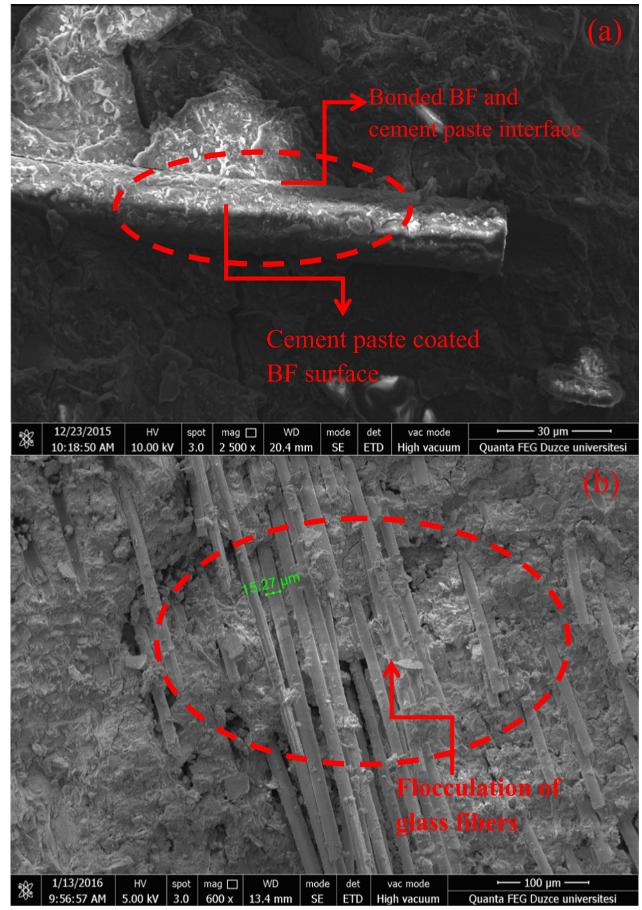


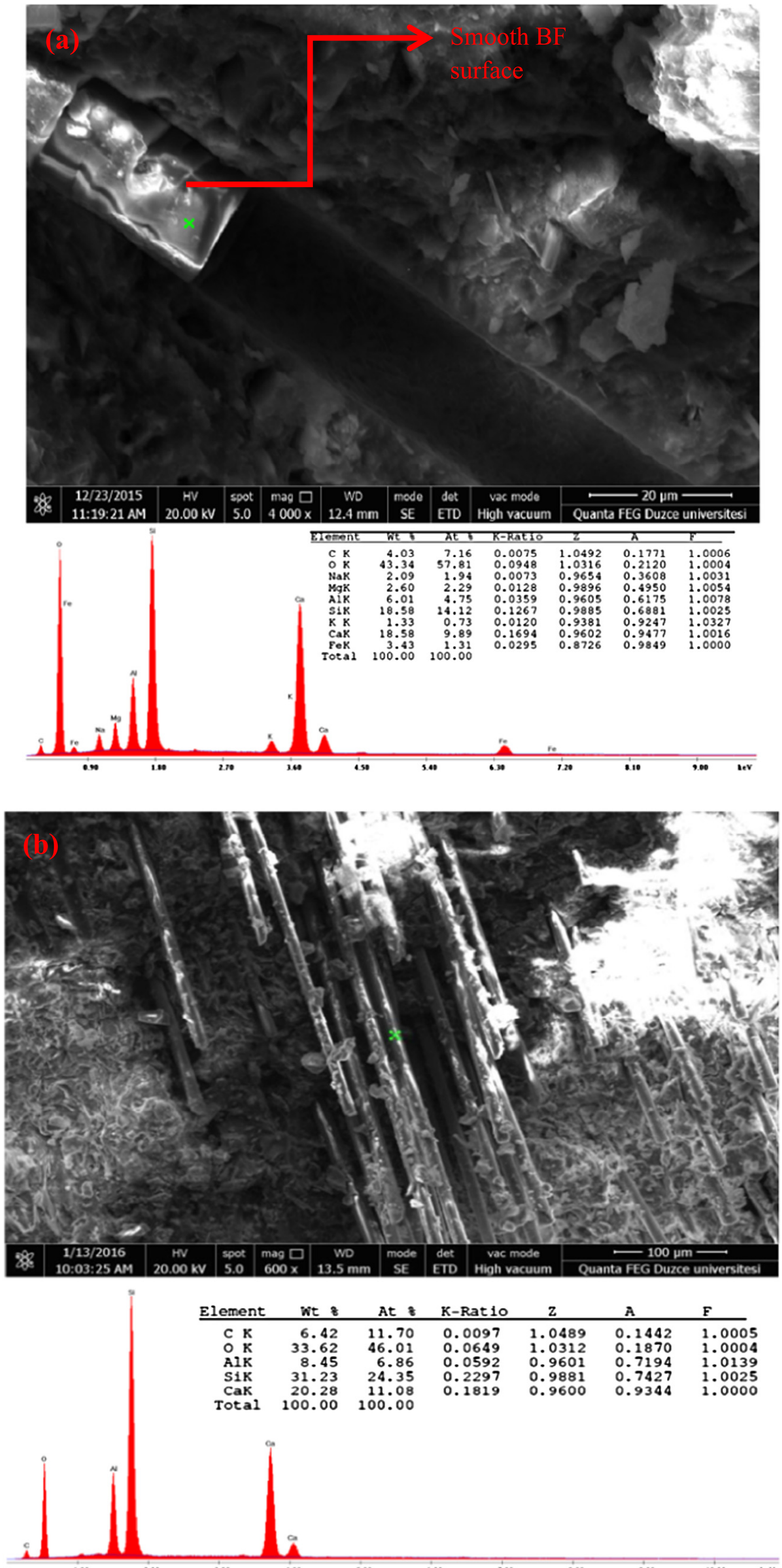
Fig. 13. SEM image (1000×) of the BFRC-24-2 (a) and GFRC-24-2 (b) test specimens.

cement paste coated BF surfaces indicate existence of bond between cement paste and BF. Increases in flexural and splitting tensile strength also indicate contribution of BF on bond strength. On the other hand, none of BFs ruptured, since its high tensile strength. Fig. 13b shows that GFs have tendency of flocculation. However, this result does not necessarily mean that all the mixtures have the same flocculation problem. Increase in fracture energy for GFRC mixtures supports this comment. On the other hand, another conclusion is that producing of GFRC should be made more carefully to prevent flocculation of the fibers. For BFRC mixtures, flocculation was not observed.

EDX result given in Fig. 14a show the composition of the BF predominantly contains Si, from the large Si peaks. Composition of BF also contains Al, Ca and Mg. Moreover, some gaps at interfacial transition zone stemming from the imperfect bond between BF and cement paste were observed. In the Fig. 14b EDX result of GF is illustrated. GF composition is also predominantly composed of Si. Other components of GF are Al and Ca.

Table 3
Mechanical properties and fracture energy values of the specimens.

Concrete code	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Fracture energy (N/m)	Modulus of elasticity (MPa)
Ref	43.98	3.65	5.44	68.28	33,100
BF-24-0.5	46.69	3.99	6.18	72.98	34,300
BF-24-1	45.28	3.92	6.10	78.94	36,400
BF-24-2	46.45	4.02	6.82	87.79	36,800
BF-24-3	47.17	3.85	5.74	85.54	37,300
GF-24-0.5	45.59	3.79	5.99	73.55	33,700
GF-24-1	45.83	3.99	6.85	96.06	33,900
GF-24-2	44.89	3.85	5.88	85.19	33,100
GF-24-3	43.41	3.62	5.11	72.07	31,500



Element	Wt %	At %	K-Ratio	Z	A	F
C K	4.03	7.16	0.0075	1.0492	0.1771	1.0006
O K	43.34	57.81	0.0948	1.0316	0.2120	1.0004
NaK	2.09	1.94	0.0073	0.9654	0.3608	1.0031
MgK	2.60	2.29	0.0128	0.9896	0.4950	1.0054
AlK	6.01	4.75	0.0359	0.9605	0.6175	1.0078
SiK	18.58	14.12	0.1267	0.9885	0.6881	1.0025
K K	1.33	0.73	0.0120	0.9381	0.9247	1.0327
CaK	18.58	9.89	0.1694	0.9602	0.9477	1.0016
FeK	3.43	1.31	0.0295	0.8726	0.9849	1.0000
Total	100.00	100.00				

Element	Wt %	At %	K-Ratio	Z	A	F
C K	6.42	11.70	0.0097	1.0489	0.1442	1.0005
O K	33.62	46.01	0.0649	1.0312	0.1870	1.0004
AlK	8.45	6.86	0.0592	0.9601	0.7194	1.0139
SiK	31.23	24.35	0.2297	0.9881	0.7427	1.0025
CaK	20.28	11.08	0.1819	0.9600	0.9344	1.0000
Total	100.00	100.00				

Fig. 14. EDX result of BF and GF.

4. Conclusions

In this study, mechanical properties, fracture behaviors and microstructure of BFRC and GFRC mixtures were determined. Three-point bending tests were performed on notched beams produced using BFRCs and GFRCs with 0.5, 1, 2 and 3 kg/m^3 fiber contents in order to compare the value of fracture energies. Based on the results of this investigation, the following conclusions can be made:

- There is no significant effect of different fiber types (Basalt and Glass) and fiber contents (0.5, 1, 2 and 3 kg/m^3) on compressive strength of BFRC and GRFC. Moreover, compressive strength increased for all specimens compared to Ref except for GFRC-24-3 mixture. Maximum 7% increase occurred in BFRC-24-3 compared to Ref specimen.
- BRFC and GFRC specimens did not separate out during splitting tensile strength test after first cracking unlike Ref specimen. It is thought that these result stems from contribution of fiber addition on ductility of Ref exhibiting brittle failure. In addition BFs and GFs increased the splitting tensile strength of the mixtures but for GFRC-24-3. Maximum increase (10%) occurred in BFRC-24-2 compared to Ref specimen. However, the increase in splitting tensile strength began to decrease for BFRC-24-3 and GFRC-24-2 specimens.
- BF and GF addition considerably increased flexural strengths of BFRC and GFRC with respect to Ref specimen. Increases in flexural strengths are more apparent for GFRC-24-1 and BFRC-24-2 concrete mixtures. Highest flexural strengths occurred for BFRC and GFRC mixtures were 6.85 MPa and 6.82 MPa, respectively. Decrease in flexural strength more distinctive for GFRC-24-2, GFRC-24-3 and BFRC-3 test specimens.
- BF and GF addition considerable increase the G_f of test specimens compared to Ref specimen. A slight drop in fracture energies were started after BFRC-24-1 and GFRC-24-2 test specimens. The highest G_f was obtained for GFRC-24-2 (96.06 N/mm) and BFRC-24-1 (87.79) test specimens. These values are almost 35% higher than those of Ref notched beam specimens. This result indicates that BFs and GFs increase ductility and energy dissipation capacity of plane concrete.
- There is no significant effect of fiber types and fiber contents on modulus of elasticity of BFRC and GRFC. Modulus of elasticity values are around 31,500–37,300 MPa and the highest value was obtained in BF-24-3 test specimen. These values are parallel to the compressive strength results. Decreases in modulus of elasticity are more apparent for BFRC concrete mixtures.
- SEM image of BFRC specimen shows that BF has been partly coated with cement paste although it has smooth surfaces. Even if it is not possible to mention about perfect bonding because of the slippage of BF from cement paste, cement paste coated BF surfaces indicate existence of bond between cement paste and BF. Increases in flexural and splitting tensile strength also indicate contribution of BF on bond strength. In addition, for BFRC mixtures, flocculation was not observed.
- SEM image of GFRC specimen shows that GFs have tendency of flocculation. However, this result does not necessarily mean that all the mixtures have the same flocculation problem. Increase in fracture energy for GFRC mixtures supports this comment. Another conclusion is that producing of GFRC should be made more carefully to prevent flocculation of the fibers.

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