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RESEARCH ARTICLE

Effects of glass fiber usage on fracture energy and mechanical behavior of concrete: An experimental approach

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Abstract

In this study, the fracture and mechanical behavior of glass fiber reinforced concrete (GFRC) are investigated comparatively. For this purpose, three-point bending tests were carried out on notched beams produced using GFRC with 1, 2, and 3 kg/m^3 fiber contents and the dimension of 6, 12, and 24 mm to determine the fracture energy. Fracture energy values of the GFRC specimens were calculated by analyzing load versus crack mouth opening displacement (CMOD) curves. Compressive strength was determined using cube samples with the dimension of 150×150mm. Tensile strength and Modulus of elasticity were determined using notched beams with the dimensions of 480×100×50 mm. Also, notched beams were produced and tested in accordance with RILEM recommendations. In addition, microstructural analyses were performed based on Scanning Electron Microscopy and Energy-Dispersive X-ray Spectroscopy examinations. The results showed that the effects of fiber contents on fracture energy were very significant. However, the effect of fiber addition on the compressive strength and modulus of elasticity values was not significant.

1. Introduction

Concrete is one of the most preferred used building materials because of its easy availability, simple production processes, and relatively low cost [1-5]. Even if, concrete has high compressive strength, its low tensile strength energy dissipation capacity, cracking resistance, and deformation capacity also affect the mechanical and fracture behaviors of concrete. [3,4,6-9]. Many different fibers are used to improve the ductility of cement-based composites. These fibers, which are randomly distributed in the concrete, govern the stress distribution, crack widths, and fracture mode of the concrete [1,10-15]. In addition to these advantageous properties, the effect of fiber addition on the compressive strength of concrete is still unclear. It is not surprising to encounter the positive contribution of fibers to the compressive strength of concrete or vice versa [16-21]. Although some researchers have determined that the fibers used in concrete slightly reduce the compressive strength, some research infers just the opposite. [22,23].

There are many different fibers used to increase the mechanical properties of cementitious composites. Glass, carbon, basalt, aramid, steel, and polypropylene are widely used fibers in the construction sector [24,25]. Glass fibers improve the mechanical properties of concrete under both static and dynamic loads [26].

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Studies show that the use of glass fiber prevents shrinkage cracks and improves the bending strength of structural elements [27,28]. In another study, it was found that glass fiber improved usability and mechanical properties with recycled aggregate [29]. In a study on the physical and durability properties of fiber reinforced concretes exposed to high temperatures, it was determined that the use of fiber caused a decrease in the durability properties, although it improved the physical properties [30]. Glass fiber has a high modulus of elasticity and is extremely durable. In this way, it can form extremely strong bonds with concrete and it can be advantageous to use with steel fibers [31].

Fracture energy is an important parameter for comparing the ductility of concretes. There are different models used for determining fracture mechanisms. Fictitious Crack Model (FCM) proposed by Hillerborg is a widely used fracture mechanics model for analysis [32,33]. The fracture energy (G_f) can be defined as the energy required to fully expand a crack. RILEM [34] and Peterson [35], proposed a suitable method for calculating fracture energy by a three-point bending test on notched beam samples.

Although there are many studies on the effect of concrete behavior using different fiber types, studies on the fracture energy of fiber reinforced concretes are ongoing. [2,36-42]. Therefore, the main purpose of this study is to determine the mechanical properties and fracture behavior of concretes containing glass fiber in different proportions and lengths. To determine the fracture energies, a three-point flexural strength test was carried out on the samples, which were produced as pre-notched beams.

2. Experimental study

2.1. Materials and specimen preparation

In this study, CEM I 42.5R Portland Cement was used in the production of GFRC in different sizes and ratios. The water/cement ratio was kept constant at 0.50 in all mixtures. To achieve the appropriate workability, 1% water-reducing and hyper-plasticizing additives were used in the mixtures by the cement weight. The coding type of the specimens in the study is given in Fig. 1. The reference mixture (without fiber) is denoted by the abbreviation "REF". Details of the mixtures are given in Table 1.

To determine the fracture energy values of the reference and GFRC specimens, beams with the dimensions of 480×100×50 mm were produced. Three-point bending test was performed on the produced beams. According to RILEM, the notch height beam height ratio (a_0/d) is equal to 0.3 and the free span beam height ratio (S/d) is equal to 4. Details of notched beams are given in Fig. 2. In addition, cube samples with the dimensions of 150×150×150 mm were produced to determine the compressive strength of the specimens.

To improve the mechanical and fracture behavior of GFRC specimens, 6, 12, and 24 mm chopped AR-Glass fibers were used. The reason for choosing given fiber lengths is that they are frequently used in the literature [30,43-55]. Some mechanical and physical properties of glass fiber are given in Table 2 and the image of glass fiber is given in Fig. 3.

Fig. 1. Listing of specimen codes

Table 1. The mixture proportion of the concretes

Concrete code	Fiber length (mm)	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)	Superplasticizer (kg/m^3)
REF	-	-					
GFRC-6-1		1					
GFRC-6-2	6	2					
GFRC-6-3		3					
GFRC-12-1		1	350	0.5	539.4	1258.6	3.5
GFRC-12-2	12	2					
GFRC-12-3		3					
GFRC-24-1		1					
GFRC-24-2	24	2					
GFRC-24-3		3					

Table 2. Some Mechanical and physical properties of glass fibers

Tensile Strength (MPa)	3400
Modulus of elasticity (GPa)	77
Elongation (%)	2.65
Diameter (μm)	13-15
Density (g/cm^3)	2.60

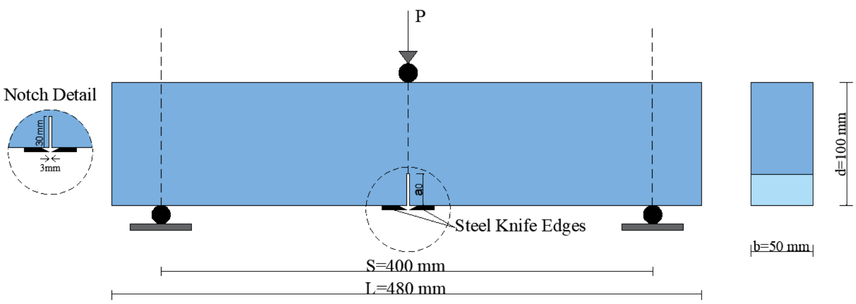


Fig. 2. Specimen details

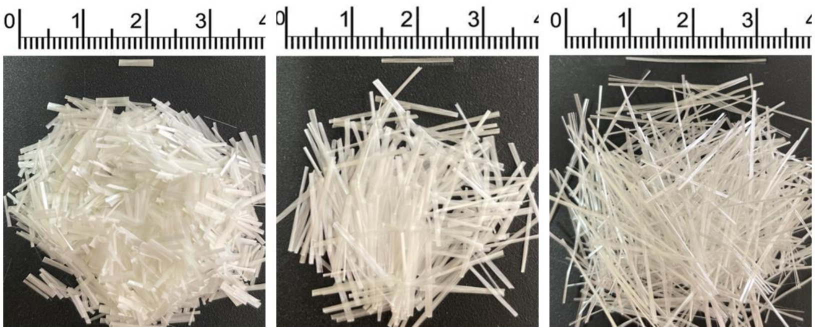


Fig. 3. Glass fibers

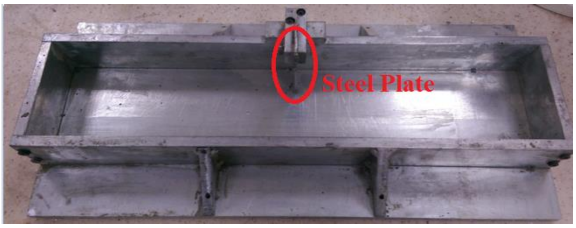


Fig. 4. Steel mold used for producing notched beam test specimens

In the production of the notched beam specimens, steel molds with a plate to form a notch in the middle of the specimen were used. In this way, notches were created during production without the need for subsequent cutting of the samples. The image of the molds is given in Fig. 4.

2.2. Methods

The compressive strength test (28 days) was performed on three cube samples produced in 15×15×15 cm dimensions. The three-point bending test, which was carried out to determine the fracture energy, was performed with a deformation-controlled electromechanical universal test device. (Fig. 5). Loading speed of the three-point bending test was determined as 0.009 mm/min. For all the specimens end of the test was determined as a 95% drop in peak load.

The CMOD was measured with the aid of a double-bladed clip-on gauge inserted into the pre-dropped notch mouth. The fracture energy was calculated using equation (1) with the recommendation of RILEM [34].

$$G_f = \frac{W_0 + mg\delta}{A} \tag{1}$$

where W_0 is the area under the load-CMOD curve (Nmm), mg is the self-weight of the specimen between supports (kg), δ is the maximum displacement (m), and δ is the fracture area $b(d - a_0)$ (m^2) where b and d are the width and height of the beam, respectively.

The flexural strength of the GFRC specimens was calculated using equation (2).

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

where P is the maximum load, S is the span length, b is the width of the specimen, d is the height of the specimen, and a_0 is notch depth. The modulus of elasticity (E) of the GFRC is calculated from the measured initial compliance C_i of the load-CMOD curve using Eq.(3) [56-59].

$$E = \frac{6Sa_0V_1(\alpha)}{(C_i bd^2)} \tag{3}$$

where $V_1(\alpha)$ is a function depending on $\alpha = (a_0 + h_0)/(d + h_0)$ and h_0 thickness of steel knife edge, and given by

$$V_1(\alpha) = 0.76 - 2.38\alpha + 3.87\alpha^2 - 2.04\alpha^3 + 0.66/(1 - \alpha)^2 \tag{4}$$

3. Results and discussion

The average compressive strength values of GFRCs of the cube specimens are given in Fig. 6 and Table 3. It is seen that the compressive strength decreases with the increase of the fiber amount. In addition, the increase in fiber length resulted in a slight decrease in compressive strength. It is thought that the fibers in concrete may not be sufficiently effective on compressive strength, but may be effective in increasing ductility at compression fracture. Some of the studies on the compressive strength effect of fiber use have positive and some negative results and the effect of fiber on compressive strength is still discussed. For this reason, some researchers have determined that the use of fibers can slightly increase or decrease compressive strength. These studies support the current study [16-23].

Three-point bending strength test results of GFRC specimens are given in Fig. 7 and Table 3. When Fig. 7 is examined, it is seen that the flexural strength of the fiber increases compared to the reference specimen. The flexural strengths increased with the increase of fiber content in all series. It is evident that the addition of glass fiber also increased the ductility of the reference specimen. Babar ve Qureshi [45] found in their study that different glass fiber amounts make a positive contribution to the flexural strength of concrete. In their mechanical tests, they reported that the addition of glass fiber showed the greatest positive effect on flexural strength.

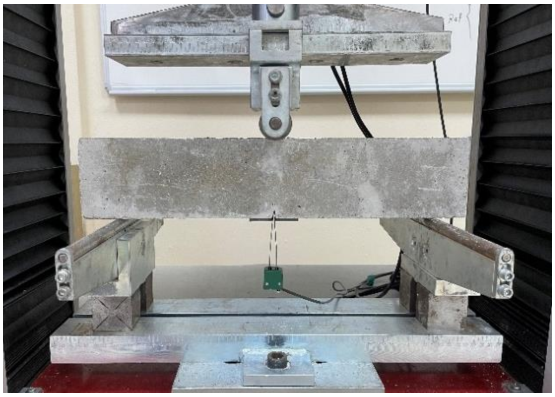


Fig. 5. Three-point bending test set-up

Table 3. Compressive strength and flexural strength test results

Concrete code	Compressive strength (N/mm^2)	Flexural strength (N/mm^2)
REF	63.02	4.95
GFRC-6-1	62.16	5.76
GFRC-6-2	60.26	6.57
GFRC-6-3	59.76	7.05
GFRC-12-1	59.67	6.41
GFRC-12-2	56.91	6.94
GFRC-12-3	53.01	7.15
GFRC-24-1	52.74	5.15
GFRC-24-2	51.88	5.81
GFRC-24-3	50.74	6.89

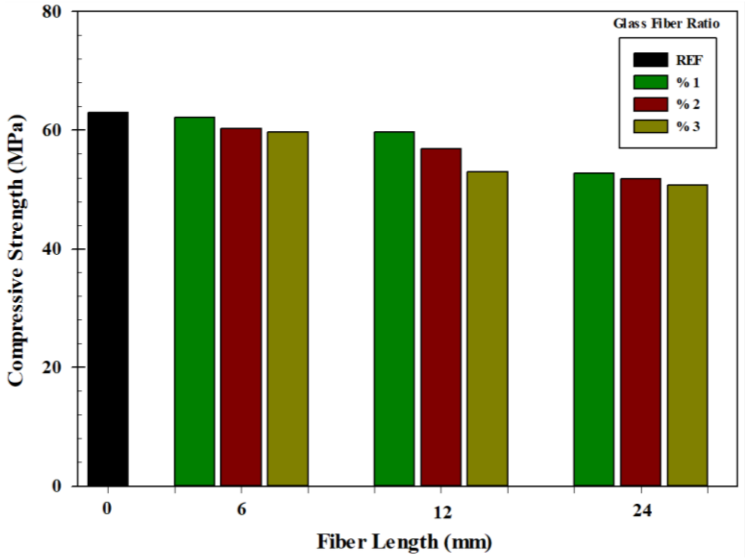


Fig. 6. Compressive strengths of the mixtures

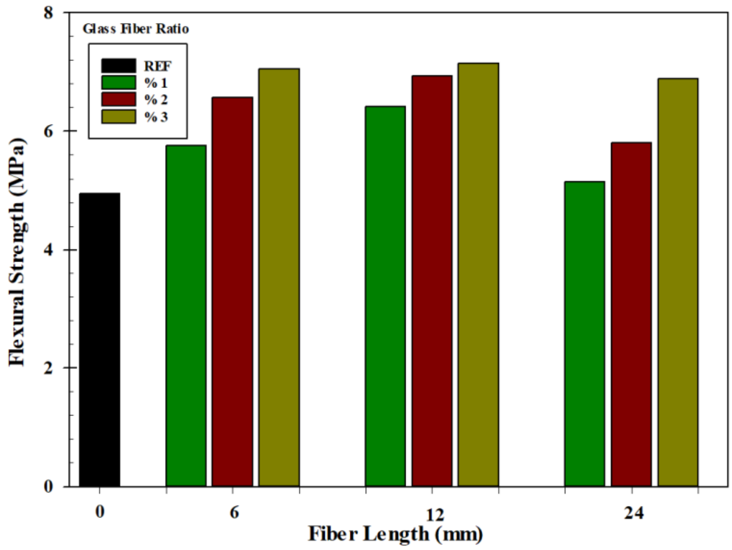


Fig. 7. Flexural strengths of the mixtures

According to Fig. 7, the increases in flexural strength are much more apparent for GFRC-6-3, GFRC-12-3, and GFRC-24-3 specimens. The flexural strengths increased by 16% (GFRC-6-1), 33% (GFRC-6-2), 42% (GFRC-6-3), 30% (GFRC-12-1), 40% (GFRC-12-2), 44% (GFRC-12-3), 3% (GFRC-24-1), 17% (GFRC-24-2) and 39% (GFRC-24-3), respectively, compared to the reference specimen. The greatest flexural strength value was obtained from the GFRC-12-3 sample with 7.15 MPa.

Load-CMOD and dissipated energy-CMOD curves obtained from the three-point bending test on GFRC specimens are given in Fig. 8 comparatively. Load-CMOD curves were drawn separately to evaluate different series among themselves in more detail. In addition, the Load-CMOD curve of all series is given together to make a relative comparison between fiber length and fiber ratio.

Dissipated energy (W_0) values of GFRC specimens are given in Fig. 9. According to Fig. 8 and Fig. 9, the addition of glass fiber increases the flexural load-carrying capacity compared to the reference specimen.

Energy dissipation and ductility of glass fiber-reinforced concrete are affected by differences in fiber types and fiber ratios. When the literature is examined, there is different information about the effect of fiber type and amount on the energy dissipation and ductility of cementitious composites [24,33].

The fracture energy values (G_f) of GFRC specimens are given in Fig. 10. It is seen that the use of glass fiber increases the fracture energies of all the other series compared to the reference specimen. GFRC-6-3 and GFR-24-3 specimens showed the best performance in terms of fracture energy. Considering the fracture energy values, it was determined that the use of glass fiber increased the energy dissipation capacity and ductility of the notched samples. In different studies in the literature, it has been determined that the use of fiber in concrete increases the fracture energy and energy dissipation capacity and limits the formation of cracks. [24,36, 60-64].

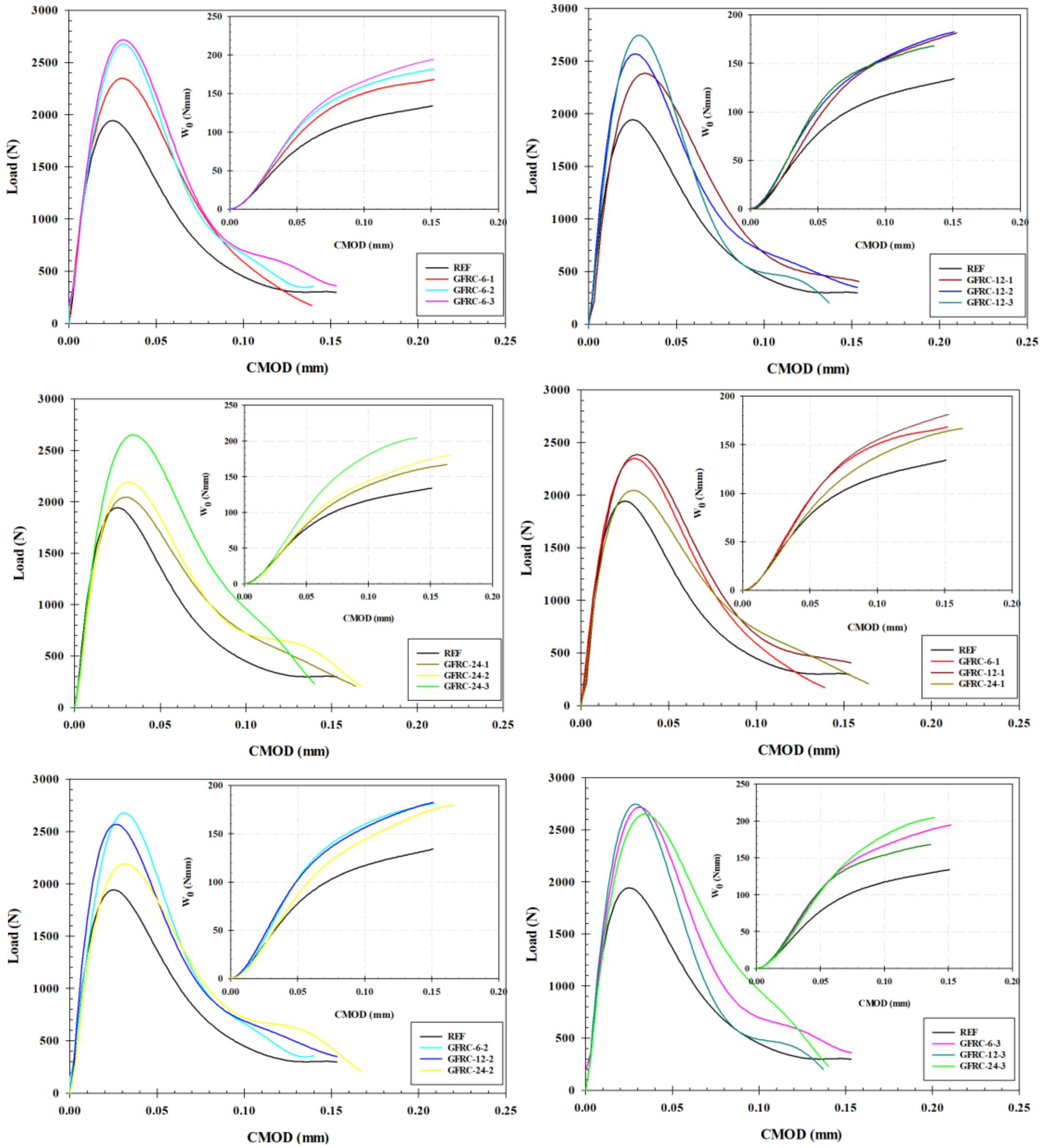


Fig. 8. Load-CMOD responses of three-point bending tests and change of W_0 corresponding to CMOD

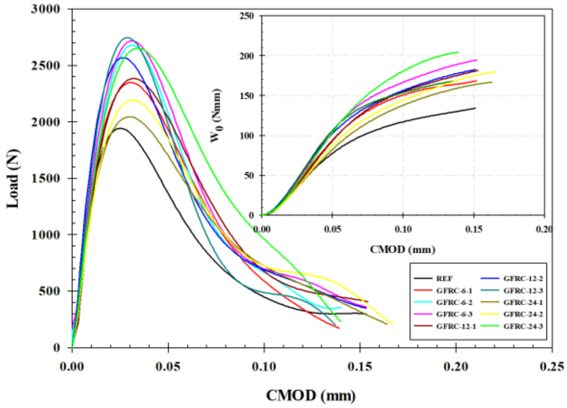


Fig. 8. Continued

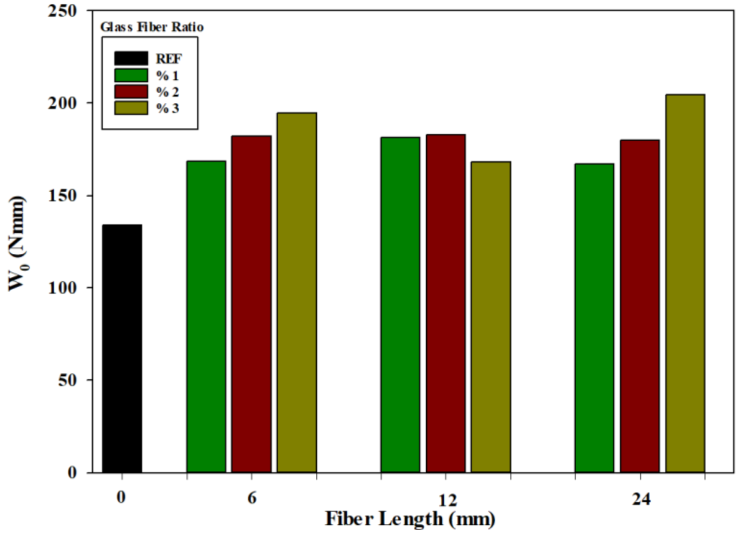


Fig. 9. Calculated W_0 values of notched beam specimens

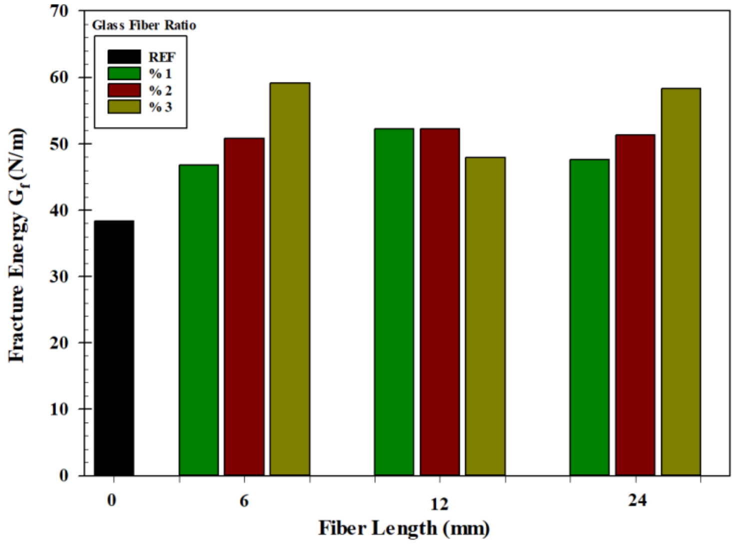


Fig. 10. Fracture energies of notched beam specimens

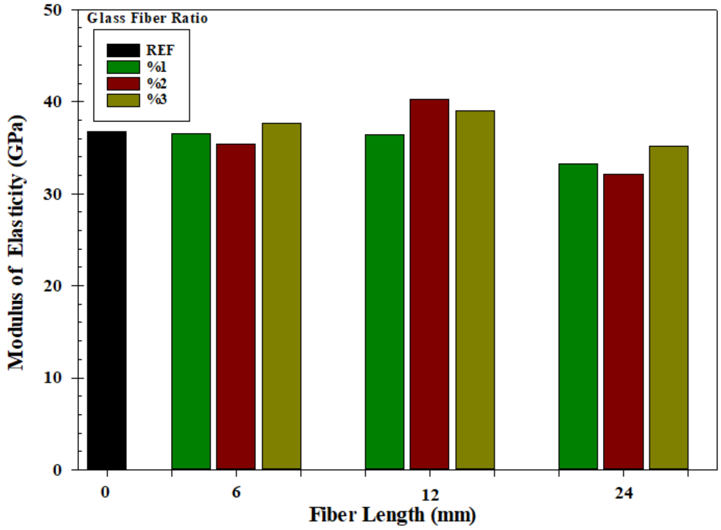


Fig. 11. Modulus of elasticity values calculated using three-point bending test results

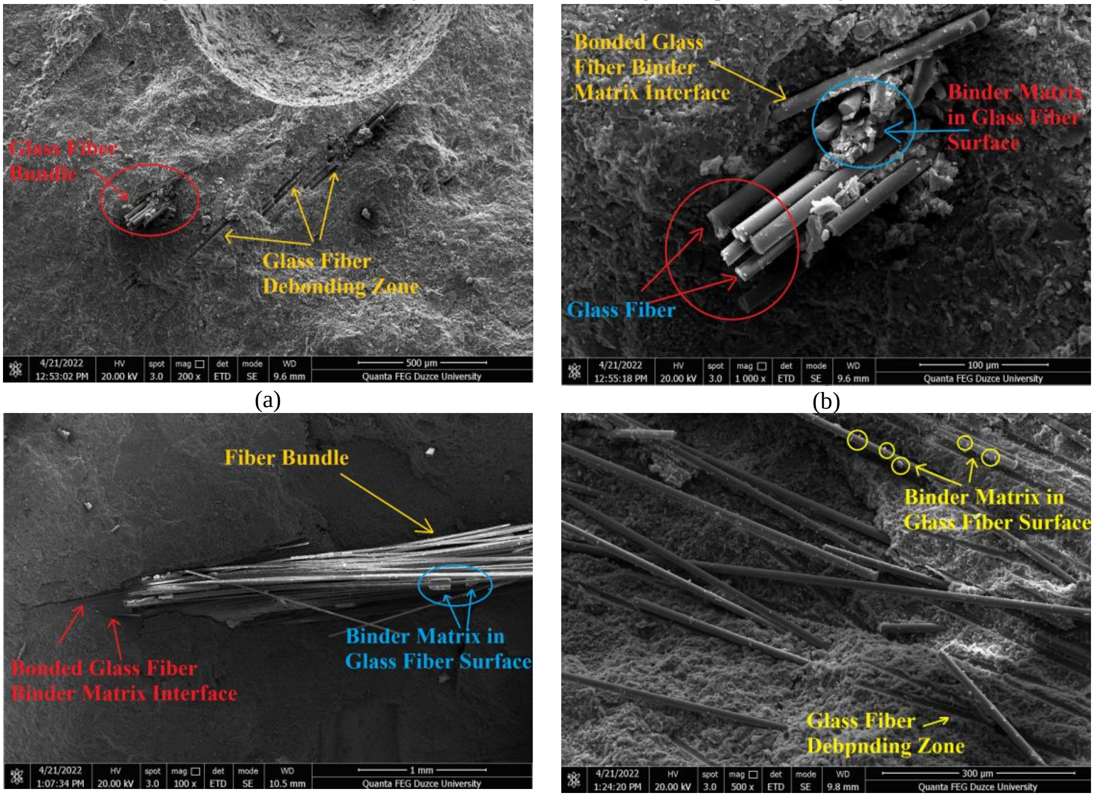
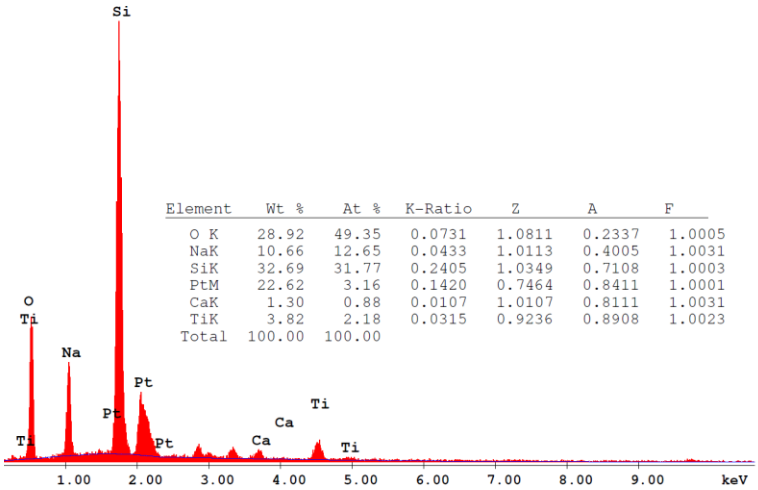


Fig. 12. SEM-EDX images of the specimens



(e)

Fig. 12. Continued

The elastic modulus values of the GFRC specimens calculated by using the three-point bending test results are given in Fig. 11. It is seen that the results are in parallel with the compressive strength values. It has been determined that the modulus of elasticity values vary between approximately 35-40 GPa. GFRC-12-2 series samples showed the best performance.

SEM-EDX analyses were performed on samples taken from the crack region. SEM images of GFRC specimens are given in Fig. 12. The relationship between glass fibers and cement matrix is seen. Although the glass fibers have a smooth surface, the cement paste attached to its surface is seen in Fig. 12b and Fig. 12d. It is seen in Fig. 12a that the fibers are debonded from the cement paste. Although it is not possible to say that there is a perfect adhesion between the fibers and the cement paste, the existence of a bond between the fiber and cement can be proved by the cement paste residues on the glass fibers. In addition, it is possible to say that glass fibers tend to flocculate (Fig. 12c). According to the EDX result (Fig. 12e), it was determined that the predominant component of the glass fiber was Si. Other components of glass fiber appear to be Ti, Na, and Ca.

4. Conclusions

In this study, three-point bending tests were performed on notched beams of GFRCs including 1, 2, and 3 kg/m^3 fiber contents to compare the fracture energy values. Mechanical properties, fracture behaviors, and microstructure of GFRC mixtures were determined. Based on the results of this investigation, the following conclusions can be made:

- There is no significant effect of different fiber contents (1, 2, and 3 kg/m^3) on the compressive strength of GRFC.
- Glass fiber addition considerably increased the flexural strengths of GFRC with respect to the reference specimen. The maximum flexural strength value was obtained from the GFRC-12-3 sample with 7.14 MPa.
- Glass fiber addition considerably increases the fracture energy (G_f) of test specimens compared to reference specimens. GFRC-6-3 and GFR-24-3 specimens showed the best performance in terms of fracture energy.
- There is no significant effect of fiber length and fiber contents on the modulus of elasticity of GRFC. These values are parallel to the compressive strength results.

- SEM image of GFRC specimen shows that glass fiber has been partly coated with cement paste although it has smooth surfaces. Although it is not possible to say that there is a perfect adhesion between the fibers and the cement paste, the existence of a bond between the fiber and cement can be proved by the cement paste residues on the glass fibers. In addition, for GFRC mixtures, flocculation was not observed. An increase in fracture energy for GFRC mixtures supports this comment.
- Increases in flexural strength also indicate the contribution of glass fiber to bond strength.

According to the results of the study, it is suggested that the production of glass fiber-reinforced concrete should be done more carefully to prevent the flocculation problem. It is also thought that the peeling between the glass fiber and the cement matrix can be resolved by using a surface textured fiber or by coating the fibers with a coating suitable for the matrix structure. In this way, since mechanical adherence will increase, improvements in mechanical properties are expected.

Conflict of interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Author contributions

Mehmet Emin Arslan: Supervision, Conceptualization, Methodology, Editing. Batuhan Aykanat: Investigation, Data curation, Writing-Original Draft Preparation, Writing-Reviewing and Editing. Mehmet Emiroğlu: Visualization, Investigation, Editing.

Data availability statement

The data presented in this study are available upon request from the corresponding author.

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