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Research Article

The Effect of Fiber Type on The Shear Capacity of Beams Manufactured By Using Geopolymer Concrete Based on Fly Ash

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Keywords

Beam,
Fiber,
Fly ash,
Geopolymer,
Shear capacity.

Abstract

Ordinary Portland cement is currently generally used cementitious material in the construction industry. However, it has significant drawbacks as it not only depletes natural resources but also releases a substantial amount of carbon dioxide during its production process. On the other hand, alkali-activated cement is an alternative option that is derived from raw materials like slag, fly ash, and metakaolin, which contain silicon dioxide (SiO2) and aluminum oxide (Al2O3). This study investigates the shear capacity of fibre-reinforced geopolymer concrete (GPC) beams under shear loads. In the study, the shear behavior of beams produced from fly ash-based geopolymer of three different fiber types was determined by applying a three-point shear test. Four beams of 100x100x400 mm dimensions were produced: reference, steel fiber, basalt fiber and glass fiber. The results showed that using steel fiber has the greatest impact on shear capacity. In addition, the shear capacity of fibrous samples is greater than the shear capacity of the reference sample. The steel fiber sample has 203% more shear capacity than the reference sample.

1. Introduction

The need for sustainable and long-lasting construction materials has become increasingly important in the context of modern engineering and environmental stewardship. Reinforced concrete (RC) continues to be a fundamental part of civil infrastructure due to its versatility and structural performance. However, ordinary Portland cement concrete (PCC) presents significant environmental challenges, mainly due to the substantial carbon dioxide emissions associated with cement production. As the construction industry looks for greener alternatives, fly ash-based geopolymer concrete (GPC) has emerged as a promising substitute, providing both reduced environmental impact and improved material properties [1-4].

Geopolymer concrete, made from industrial by-products like fly ash, is created through the polymerization of aluminosilicate materials activated by alkaline solutions. This innovative binding system not only diverts waste from landfills but also significantly reduces the carbon footprint compared to conventional PCC. In addition to its environmental benefits, GPC demonstrates excellent mechanical properties, thermal resistance, and durability, making it an appealing option for structural applications [4-7].

At the same time, the incorporation of fiber reinforcements into concrete has attracted significant interest for its potential to enhance various mechanical characteristics, including tensile strength, ductility, and crack resistance. Among the various types of fibers, steel, glass, and basalt fibers have shown considerable promise. Steel fibers are well-known for their high tensile strength and ability to bridge cracks, thereby improving the post-cracking behavior of concrete. Glass fibers contribute to improved durability and resistance to chemical attacks, while basalt fibers, a relatively newer addition, offer exceptional thermal stability, corrosion resistance, and an optimal balance of mechanical properties [8-10].

Fly ash, a residue from coal combustion in power plants, contains aluminosilicate compounds crucial for the geopolymerization process. These compounds interact with alkaline activators like sodium hydroxide and sodium silicate to create the geopolymer binder, which functions similarly to ordinary cement by binding aggregate particles together. The incorporation of fly ash in GPC aids in waste management, lessening the environmental impact of fly ash disposal. Geopolymer concrete production significantly reduces carbon dioxide emissions compared to conventional Portland cement production, a major source of industrial CO_2 emissions. By utilizing fly ash, the sustainability profile of GPC is further improved through waste recycling. GPC exhibits excellent resistance to various aggressive chemicals, making it suitable for challenging environmental conditions. The compact microstructure of GPC, influenced by fly ash particles, results in decreased permeability, limiting the penetration of harmful substances such as chlorides and sulfates. Fly ash-based GPC offers good thermal stability and fire resistance, advantageous for structures exposed to high temperatures. Geopolymer concrete made with fly ash can achieve high compressive strengths, on par with or even surpassing those of ordinary concrete. The presence of aluminosilicates in fly ash contributes to the formation of a robust and durable matrix, enhancing the flexural and tensile properties of GPC. Fly ash generally enhances the workability of fresh geopolymer concrete, facilitating mixing, placing, and finishing. The setting time of GPC can be adjusted by varying the proportions of fly ash and alkaline activators, providing flexibility in construction schedules and applications. Using fly ash as a raw material for geopolymer concrete can be cost-effective, particularly in areas where fly ash is abundant and cost-efficient compared to Portland cement [11-13].

Glass fibers play a crucial role in enhancing the durability of geopolymer concrete by improving its resistance to cracking and reducing permeability, thus preventing the ingress of water and harmful chemicals. They also help mitigate shrinkage cracking and improve the tensile strength of the concrete, ultimately enhancing its overall structural performance, especially when special alkali-resistant glass fibers are used to ensure long-term stability in the alkaline environment of geopolymer concrete. Steel fibers significantly increase the toughness and ductility of geopolymer concrete, allowing it to absorb more energy before failure and improving its flexural strength, crack control, and shear strength. This makes it particularly beneficial in structural applications like

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beams and slabs that are subjected to shear forces, enabling the concrete to carry higher loads and span larger distances without excessive deflection or cracking. Basalt fibers provide excellent thermal stability and resistance to high temperatures and thermal cycling, making geopolymer concrete more suitable for applications exposed to extreme temperature variations. They also exhibit good resistance to chemical and environmental corrosion, contributing to the durability and lifespan of geopolymer concrete in aggressive environments. Additionally, basalt fibers improve the tensile and flexural strength of geopolymer concrete, enhancing its overall mechanical performance due to their lighter weight and high specific strength [13-16].

The aim of this study is to experimentally examine the shear strength of geopolymer concrete beams produced from steel, glass and basalt fiber. For this purpose, beams of 100x100x400 mm dimensions were produced, one as a reference. Three-point shear test was applied to determine the shear capacity. Fly ash based geopolymer concrete was used in the study. In addition, 1% fiber by volume was used in all mixtures except the reference sample.

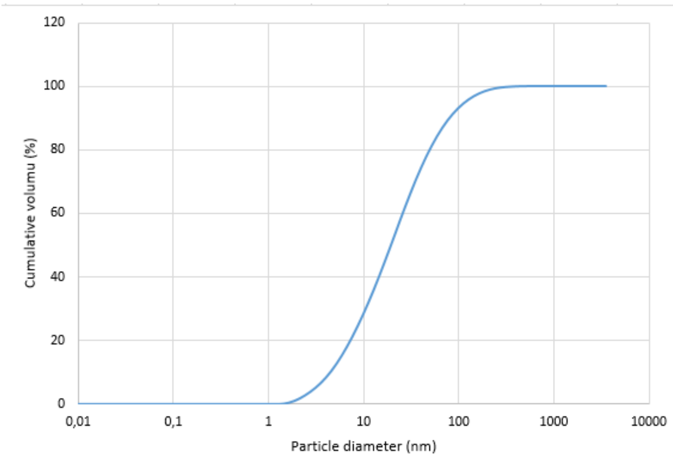
2. Testing process

2.1. Materials

F type fly ash was used to determine the effectiveness of fly ash additive in the geopolymer composite mixture. The specific gravity of the fly ash used in the mixture is 2.25 g/cm^3. The chemical properties of fly ash are presented in Table 1. The particles size analysis and XRD pattern of fly ash are shown in Figure 1.

Table 1. Chemical properties of fly ash

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O
5,7	65,6	14,6	6,6	0,9	0,2	1,1	1,5



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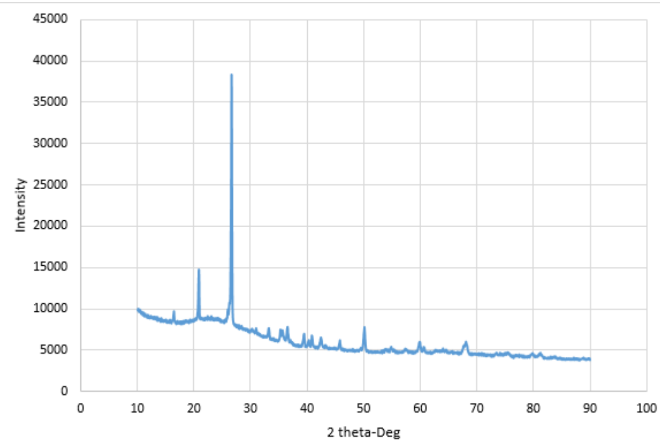

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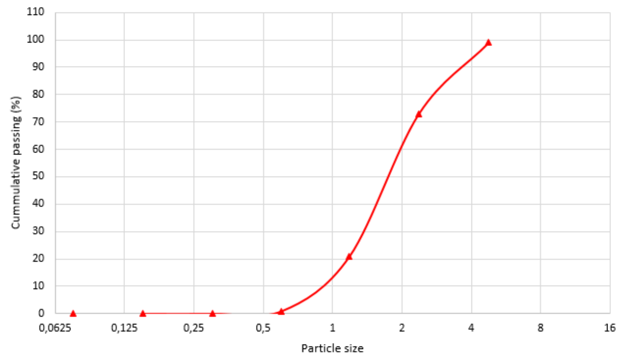
Figure 1. (a) Particles size analysis (b) XRD pattern of fly ash

Quartz material with a diameter range of 0-0.5 mm was used in the geopolymer composite mixture. Sieve analysis and XRD pattern of the quartz material used in the mixture are presented in Figure 2. The specific gravity of quartz is 2.71 g/cm^3. The chemical properties of the quartz material used are presented in Table 2.

Table 2. Chemical properties of quartz

SiO_2	Al_2O_3	Fe_2O_3	MgO
98,2	11,4	0,2	<0,1



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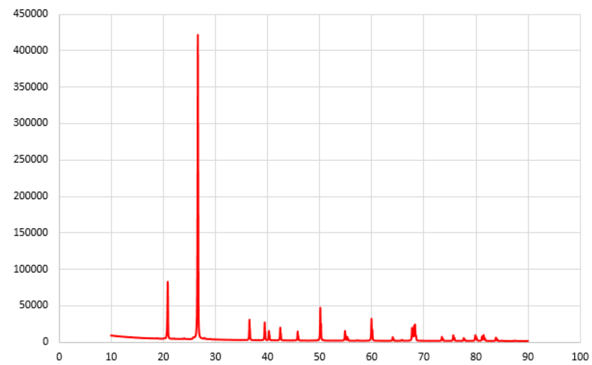

(b)

Figure 2. (a) Particles size analysis (b) XRD pattern of quartz

Fine aggregate was also used in the geopolymer composite mixture. The fine aggregate used in the mixture was obtained from the readymixed concrete plant and its specific gravity is 2.65 g/cm³. The granulometry curve drawn as a result of fine aggregate sieve analysis is presented in Figure 3.

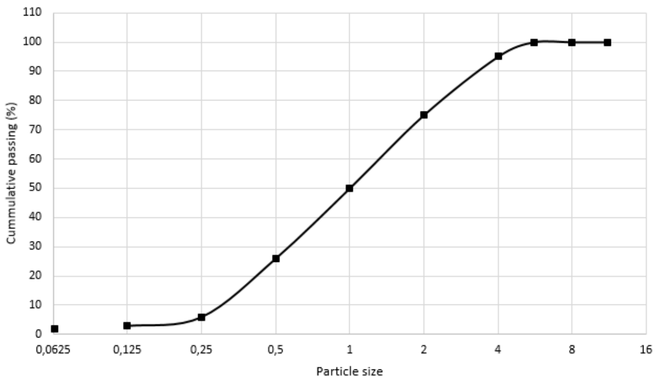


Figure 3. Particles size analysis of fine aggregate

Sodium silicate and sodium hydroxide were used as alkaline activators in the geopolymer composite. Sodium silicate and sodium hydroxide were used in the mixture to start the geopolymer composite reactions. Additionally, the ratio of sodium silicate to sodium hydroxide in the mixture was taken as 2,5. As a result of the preliminary castings, a ratio of 2.5 was decided for both adequate machinability and sufficient strength. The chemical properties of sodium hydroxide and sodium silicate used as alkaline activators in the geopolymer mixture are presented in Table 3 and Table 4.

Table 3. Chemical properties of sodium hydroxide

Na_2CO_3	NaOH	Cl	SO_4	Fe	Al
0,3	99	<0,01	<0,01	<0,01	<0,01

Table 4. Chemical properties of sodium silicate

SiO_2	Na_2O	H_2O	Fe
28,2	8,8	63,0	<0,01

Three different fiber types: steel, glass and basalt were used in the geopolymer concrete mixture. The technical properties of the fibers used in the mixture are presented in Table 5. Fiber was used at a rate of 1% by volume in all mixtures.

Table 5. Technical properties of fibers

	Steel fiber	Glass fiber	Basalt fiber
Length (L) (mm)	30	30	30
Diameter (d) (μm)	5	13	13
Elongation (%)	<2	4.4	4.0
Density (gr/cm²)	7,8	2.60	2.66
Tensile strength (MPa)	2000	3241	4500
Modulus of elasticity (GPa)	200	73	90

2.2. Mixture Design

The concrete mixture used in the study is presented in Table 6. Fly ash was used as the main binding material in the geopolymer concrete mixture at a dosage of 700 kg/m³. Additionally, quartz powder and sand were used as fine aggregate in the mixture. Concrete casting was done at Atatürk University Civil Engineering Building Laboratory using a 300 dm³ capacity concrete mixer. In the first step, the dry ingredients were mixed for three minutes. In the second step, alkaline activators were added and mixed for another 3 minutes. In fiber concrete samples, fibers were added to the dry mixture and mixed. Concrete was poured using molds with dimensions of 100x100x400 mm. The samples were removed from the mold 24 hours after concrete casting. It was then cured in a room temperature for 7 days.

Table 6. Mixing proportions (kg/m³)

Fly ash	Quartz powder	Fine aggregate	Sodium hydroxide	Sodium silicate
700	275	350	180	450

2.3. Sample geometry and testing

Beams with dimensions of 100x100x400 mm were used in the study. Three-point shear test was applied to investigate the shear capacities of the test samples. In the experiments, a loading rate of 20 kN/sec was applied to all samples. The three-point experimental setup is presented in Figure

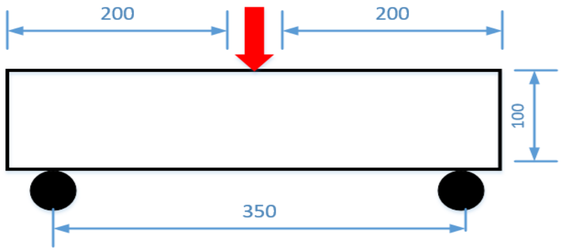


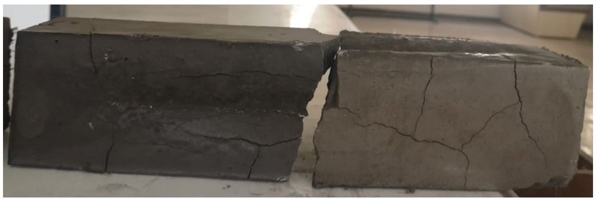
Figure 4. Schematic representation of the experimental setup

3. Results and Discussion

Experimental results are presented in Table 7. In Table 7, the maximum shear force capacity (Pmax) of the samples, the midpoint displacement value corresponding to the maximum shear force capacity (Δmax) and the ultimate displacement value at failure point (Δu) are presented. Additionally, the energy absorption capacities of the samples (E) were calculated from the area under the load-displacement curves of the samples. The maximum shear capacity was obtained in the sample using steel fiber. However, the maximum midpoint displacement value was obtained in the sample using glass fiber. The steel fiber sample has 203% more shear capacity than the reference sample. Samples using glass fiber and basalt fiber have 159.37% and 45.83% more shear force than the reference sample, respectively. The maximum midpoint displacement value was reached in the sample using glass fiber. On the other hand, the appearance of the samples after the experiment is presented in Figure 5.

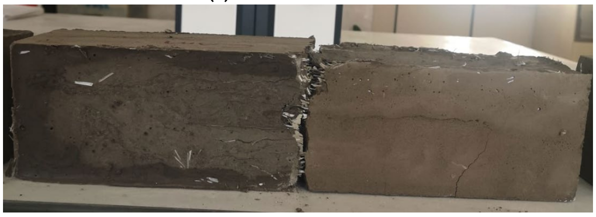
Table 7. Experimental results

	Max load (kN)	Δmax (mm)	Δu (mm)	E (kN.mm)
Reference	0,96	13,34	14,24	7,67
Steel Fiber Beam	2,91	17,69	25,01	50,93
Glass Fiber Beam	2,49	22,42	30,02	46,98
Basalt Fiber Beam	1,40	17,72	20,03	18,77



(a) Reference

(b) Steel fiber beam



(c) Glass fiber beam

(d) Basalt fiber beam

Figure 5. Photo of tested beams

The load-midpoint displacement curves of the samples are presented in Figure 6 Curves generally consist of two parts. In the first part, the samples exhibited a linear behavior. Micro cracks were observed in the beams in the linear region. At the end of the linear region, the samples reached their maximum load carrying capacity. After the maximum load value, the displacement capacity of the samples increased and the load carrying capacity decreased.

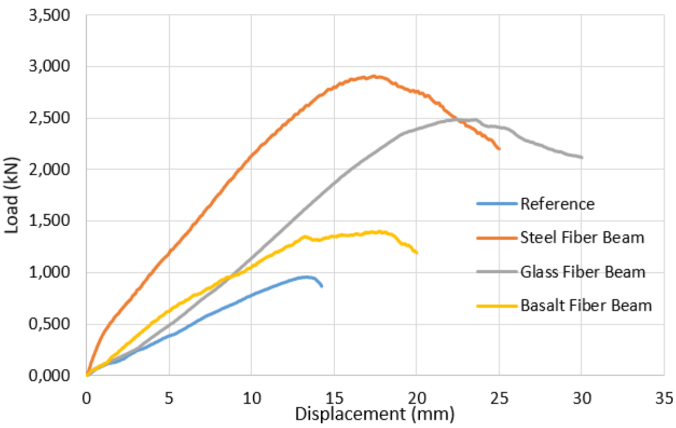


Figure 6. Load-mid-point displacement curves

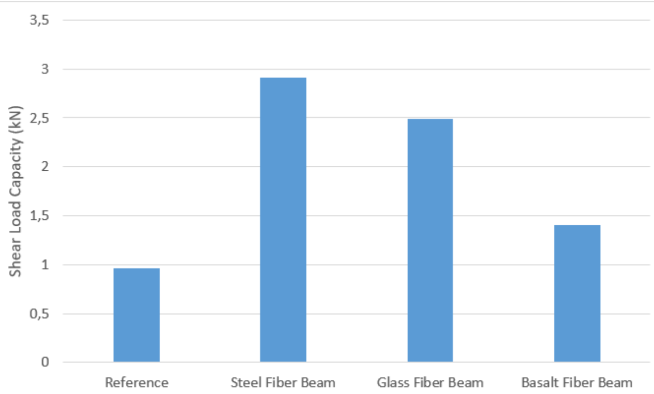


Figure 7. Maximum shear load capacity of specimens

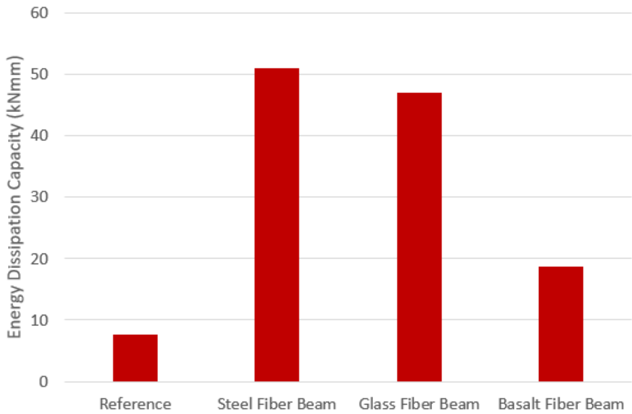


Figure 8. Energy dissipation capacity of specimens

The maximum shear force capacity of the samples is presented in Figure 7. In Figure 8, the energy absorption capacities of the samples are presented. The maximum energy absorption capacity was obtained in the sample using steel fiber. The minimum energy dissipation capacity was obtained in the reference sample. Steel fibers served as a bridge to cover the cracks in the geopolymer mixture. In addition, they helped to increase the weak principal tensile stresses of concrete. Steel fibers helped in resisting the principal tensile stresses in the concrete phase. Steel fibers helped carry the stresses to stronger areas within the concrete. In the basalt fiber sample, basalt fibers significantly reduced the workability of the geopolymer mixture. Decreased workability caused settling problems within the concrete. Thus, voids were formed in the concrete. Due to these gaps, the shear force capacity of the sample decreased.

4. Conclusion

The aim of this study is to experimentally investigate the effect of three different fiber types on the shear force capacity of fly ash-based geopolymer concrete. As a reference, other samples were made from steel, glass and basalt fiber. Three-point shear test was applied to examine the shear force capacity. As a result of the experimental study, the following results were obtained.

- The maximum shear force capacity was obtained in the sample using steel fiber. The shear force capacity of the sample using steel fiber is more than twice that of the reference sample. The minimum shear force capacity was obtained in the reference sample as expected.

- The maximum final midpoint displacement value was obtained in the sample using glass fiber. In the sample using glass fiber, it is approximately 2 times more than the reference sample. The use of glass fibers caused a significant effect on the midpoint displacement value of the samples.

- Energy dissipation capacity was calculated from the area under the shear force-midpoint displacement curves of the samples. Maximum energy absorption capacity was obtained in the sample using steel fiber. In the samples using glass and basalt fiber, 6.1 and 2.4 times more energy absorption capacity was achieved, respectively, compared to the reference sample.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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