INVESTIGATION OF THE COMPRESSIVE STRENGTH AND FRESH PROPERTIES OF MODIFIED NATURAL FIBER-REINFORCED GEOPOLYMER COMPOSITES

Research Assistant, Arif Benlioğlu (ORCID: 0000-0001-6685-2319)
Bursa Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Bursa, Turkey
E-mail: arif.benlioglu@btu.edu.tr

Associate Professor Dr., Süleyman Özen (ORCID: 0000-0001-5522-427X)
Bursa Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Bursa, Turkey
E-mail: suleyman.ozen@btu.edu.tr

Assistant Professor Dr., Yasin Altın (ORCID: 0000-0002-8554-3025)
Bursa Technical University, Faculty of Engineering and Natural Sciences, Department of Polymer Materials Engineering, Bursa, Turkey
E-mail: yasin.altin@btu.edu.tr

Professor Dr., Ali Mardani (ORCID: 0000-0003-0326-5015)
Bursa Uludağ University, Faculty of Engineering, Department of Civil Engineering, Bursa, Turkey
E-mail: alimardani@uludag.edu.tr

Abstract

In this study, the fresh-state properties and compressive strength of sisal fiber–reinforced, blast furnace slag–based geopolymer composites whose surface characteristics were enhanced with graphene oxide (GO) were experimentally investigated. Blast furnace slag was used as the aluminosilicate source in all mortar mixtures. Graphene oxide–coated and uncoated fibers with a length of 0.5 cm were added to the mixtures at volumetric ratios of 0.3% and 0.6%. A sodium hydroxide (NaOH) solution prepared at 12M concentration and sodium silicate (Na_2SiO_3) were used to activate the binder system. The silicate/hydroxide, sand/binder, and activator/binder ratios were kept constant at 2, 2.5, and 0.75, respectively. The prepared mortar samples were subjected to air curing (20±2 °C) for 28 days. The fresh properties (flow diameter) and the hardened-state property (compressive strength) of the produced mortar mixtures were examined. The results revealed that the addition of sisal fibers significantly reduced the fresh-state workability of the geopolymer mortars. Among mixtures with the same fiber content, the graphene oxide modification applied to the fiber surface increased the fresh-state properties by approximately 8–10% and significantly improved workability. The highest compressive strength, 49.04 MPa, was obtained in the SG05-06 mixture containing 0.6% graphene oxide–coated fibers. The findings indicate that sisal fiber reinforcement enhances the compressive strength of geopolymer mortars. Furthermore, surface modification with graphene oxide was observed to markedly improve strength development by reinforcing the fiber–matrix interfacial interaction. It was concluded that natural fibers can serve as a sustainable and high-performance reinforcement material in geopolymer systems when an appropriate fiber ratio and effective surface modification are employed.

Keywords: Sisal fiber, graphene oxide coating, surface improvement, fresh properties, compressive strength

1. Introduction

Portland cement is the most widely used binder in the concrete and mortar industry due to its high mechanical strength and long service life (Joshua et al 2018). Due to the high energy requirements in clinker production, intensive raw material use, and fossil fuel consumption, the cement industry is responsible for approximately 7–8% of global CO_2 emissions (Khozin et al. 2020). This situation necessitates a shift towards low-carbon footprint binder technologies as alternatives to classic Portland cement systems, with the aim of developing sustainable and environmentally friendly building materials (Zaland et al. 2026). Geopolymers, particularly C–A–S–H and N–A–S–H gel phases formed as a result of alkali activation of industrial by-products such as blast furnace slag and fly ash, stand out as low-emission and high-performance binder systems (Yip et al. 2005, Palomo et al. 2007, Lodeiro et al. 2009). These matrices offer superior properties compared to Portland cement-based systems, not only in terms of compressive and flexural strength, but also in terms of chemical and durability performance (Zhao et al. 2021, Provis et al. 2009, Duxson et al. 2007). The utilization of wastes such as blast furnace slag and fly ash holds significant potential in terms of waste management, energy efficiency, and environmental sustainability. However, the brittle behavior of geopolimer matrices, with their crack propagation and limited energy absorption capacity, constitutes a significant disadvantage in engineering applications requiring ductility (Ranjbar et al. 2020, Dias et al. 2005, Chindaprasirt et al. 2007). This low ductility level can be improved through fiber reinforcement (Alcan et al. 2025). Thanks to the crack bridging and energy dissipation mechanisms of the fibers, the toughness, deformation capacity, and impact resistance of the composite are significantly increased (Wang et al. 2025, Ravindran et al. 2018). Natural fibers, especially sisal, jute, and hemp, are emerging as a remarkable alternative for sustainable fiber reinforcement due to their renewable origin, biodegradable structure, and low density (Özen et al. 2024, Ul Haq et al. 2025). However, natural fibers exhibit a high water absorption tendency and limited chemical stability (Begum et al. 2021). High pH conditions can lead to weakening at the fiber-matrix interface and long-term strength losses. Furthermore, the tendency of fibers to clump together in fresh mixtures prevents homogeneous distribution, leading to reduced processability and decreased mechanical properties (Arpaci et al. 2025, Ramachandran et al. 2022).

In recent years, chemical and physical modification methods applied to fibers to reduce these negative effects and improve matrix-fiber interface interaction have gained importance (Thimmegowda et al. 2025, Ahmad et al. 2019). In this context, nanotechnological approaches, especially graphene oxide (GO) coating, stand out (Cecconello et al. 2023, Yao et al. 2019). GO coating strengthens the physical adhesion between the matrix and the fiber by increasing the fiber surface roughness. In addition, GO coating applied to the fiber surface reduces the tendency to absorb

water and promotes a more homogeneous distribution of fibers in the mixture, contributing to the improvement of processability properties (Islam et al. 2025). In the literature, it has been reported that natural fiber-reinforced composites with GO coating, along with appropriate fiber ratio and length, improve the mechanical properties of concrete and mortar mixtures (Özen et al. 2024).

In this study, 0.5 cm long GO-coated and uncoated sisal fibers were added to blast furnace slag-based geopolymer mortars at different volume ratios (0.3% and 0.6%). The fresh-state properties and 28-day compressive strength of the produced composites were experimentally investigated. This study aims to scientifically demonstrate the contribution of using GO-modified sisal fibers in mortars to the development of sustainable building materials and functional composites.

2. Materials and Methods

2.1. Materials

In this study, ground blast furnace slag (GBFS) was used as the main binder of the geopolimer composition (Figure 1). BFS exhibits the ability to set at room temperature due to its high CaO content. Therefore, it supports the formation of a durable matrix without the need for additional heat curing. The physical and chemical properties of BFS obtained from Kardemir Iron and Steel facilities are presented in Table 1 and Table 2, respectively.

Table 1. Some physical characteristics of ground blast furnace slag

Sieve Diameter (mm)	Passing through Sieve (%)		
0.025	75	Blaine Fineness (cm^2/gr)	4180
0.040	88	Loss on Ignition (%)	0.13
0.063	96		
0.090	99	Specific Gravity	2.79
0.125	100		

Table 2. Chemical composition of ground blast furnace slag

SiO_2 (%)	40.27
Al_2O_3 (%)	13.18
Fe_2O_3 (%)	0.75
CaO (%)	28.07
MgO (%)	7.45
SO_3 (%)	1.64
Na_2O (%)	0.61

K_2O (%)	1.04
TiO_2 (%)	1.46
MnO (%)	2.35
SrO (%)	0.07

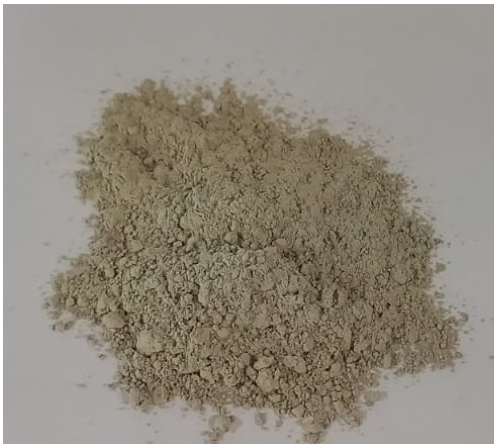


Figure 1. Images of ground blast furnace slag

In this study, 99% pure solid sodium hydroxide and sodium silicate were used as alkali activators (Figure 2). Solid sodium hydroxide was dissolved at a concentration of 12M. A study by Hamidi et al. (2016) reported that geopolymers exhibited optimal mechanical properties at a concentration of 12 M NaOH. The chemical composition of the sodium silicate and sodium hydroxide alkali activators used is shown in Table 3.

Table 1. Chemical properties of alkali activators

Chemical Composition	**Na_2SiO_3**	**NaOH**
H_2O	53.1	21.9
SiO_2	32.2	-
Na_2O	14.7	75.2

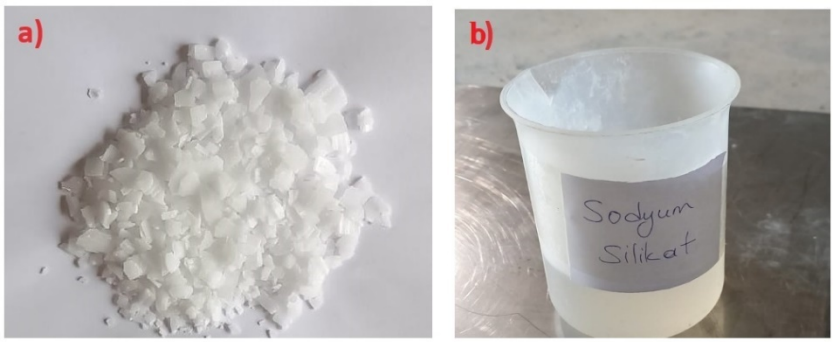


Figure 2. Alkali activators **a)** sodium hydroxide **b)** sodium silicate

CEN Standard sand aggregate with a particle size between 0–2 mm, conforming to TS EN 196-1 standard, was used. The particle size distribution of the aggregate used is given in Table 4. According to TS EN 1097-6 standard, the water-saturated surface dry specific gravity of the standard sand is 2.64 and its water absorption capacity is 0.4%.

Table 2. Particle size distribution of standard sand

Square Mesh Opening (mm)	Retained on Sieve (%)	Cumulative Passing (%)
2.00	0	100
1.60	4.32	95.68
1.00	33.98	66.02
0.50	67.11	32.89
0.16	86.85	13.15
0.08	99.83	0.17

The natural fibers used as reinforcement material in this study were obtained from the leaves of the Agave sisalana species, belonging to the Agavaceae family. Sisal fibers have a specific gravity of approximately 1.4 g/cm³ and tensile strength ranging from 400 to 800 MPa. 0.5 cm long sisal fibers were added to the mixture in volumetric percentages of 0.3% and 0.6%, both with and without GO coating (Figure 3). The graphene oxide coating process applied to the fiber surfaces aimed to strengthen the matrix-fiber interface bond and thus increase mechanical adhesion.

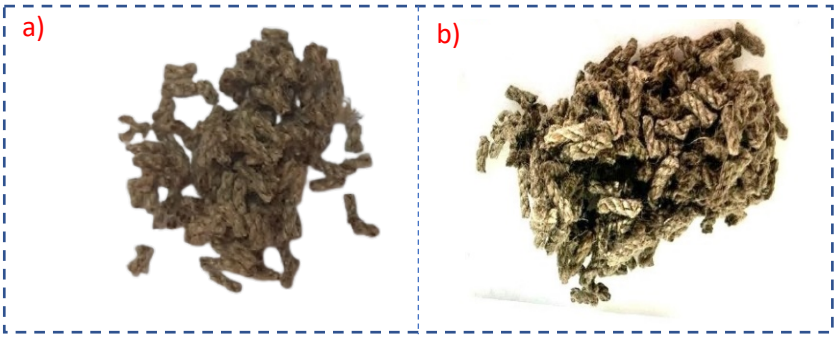


Figure 3. 0,5 cm sisal fiber **a)** without GO coating **b)** GO coating

2.2. Mix proportions

The mixtures were prepared with a sand/binder ratio of 2.5 by weight; a binder/sodium hydroxide ratio of 4; and a binder/sodium silicate ratio of 2 (Table 5). Preliminary experiments and workability analyses determined an activator/binder ratio of 0.75 (Table 5). This ratio was considered to provide the most suitable condition in terms of practical workability and matrix homogeneity. The silicate/hydroxide ratio was kept constant at 2.0 in all mixtures. Sisal fibers, 0.50 cm in length and at

two different volume ratios (0.3%-0.6%), were added directly to the mortar matrix during the preparation of the mixtures. The quantities of materials used in the preparation of the mortar mixtures are shown in Table 6.

Table 5. Fixed ratios used in the mortar mixture

Sand/Binder	2.5
Binder/Sodium Hydroxide	4
Binder/Sodium Silicate	2
Silicate/Hydroxide	2
Activator/Binder	0.75

Table 6. Mortar mixture quantities

Mixture	Fiber Content (%)	Fiber Length (cm)	GBFS (gr)	Sand (gr)	Sodium Silicate (gr)	Sodium Hydroxide (gr)	Fiber (gr)
Control	-	-	450	1125	225	112,5	-
S05-03	0,3	0,5	450	1125	225	112,5	3,49
S05-06	0,6		450	1125	225	112,5	6,98
SG05-03	0,3	0,5	450	1125	225	112,5	3,49
SG05-06	0,6		450	1125	225	112,5	6,98

In the first stage, the binder (YFC) and alkaline activators were mixed in a laboratory-type mortar mixer at 65 rpm for 30 seconds. This resulted in a homogeneous pre-mix. Then, aggregate and uncoated sisal fibers were added to the mixture in the specified proportions. In this stage, the mixture was mixed again, first at 65 rpm for 30 seconds, and then at 125 rpm for another 30 seconds, to ensure a homogeneous distribution of both the fibers and aggregate particles. After the mixing process was completed, the fresh mortar was placed into molds with a spatula, and the samples were cured at room temperature for 28 days. A schematic representation of the mortar mixing procedure is presented in Figure 4.

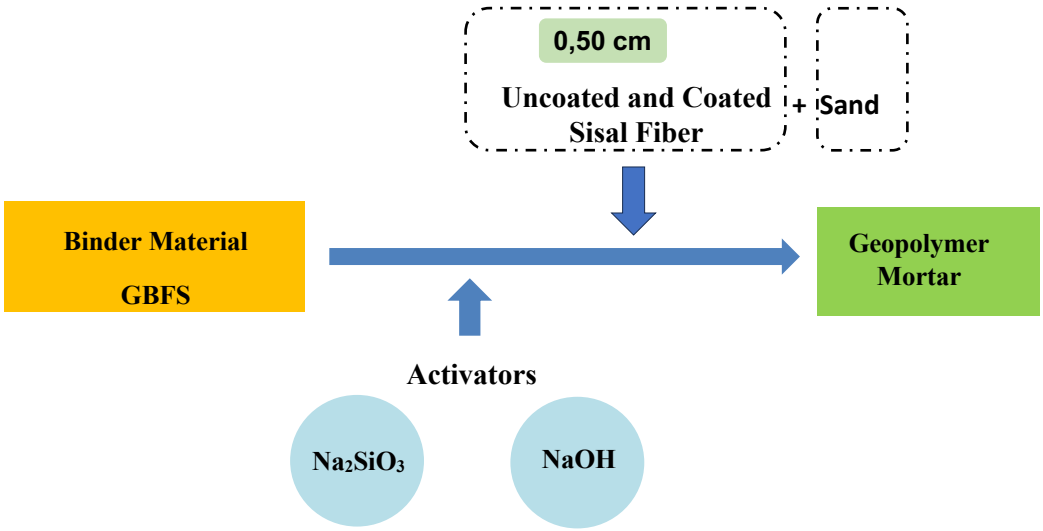


Figure 4. Schematic representation of the mortar mixing Procedure

2.3. Methods

The workability characteristics of mortar mixtures were determined according to the slump-flow test specified in the ASTM C1437 standard. In this method, freshly alkali-activated mortar mixture was placed in two layers in a conical mold with a base diameter of 100 mm. After carefully removing the mold, the spreading plate was dropped freely 25 times for 30 seconds. At the end of the experiment, the diameters of the spreading mortar in two perpendicular directions were measured, and the arithmetic mean of these two values was determined as the spread value. The spreading plate used in the experiments is shown in Figure 5.

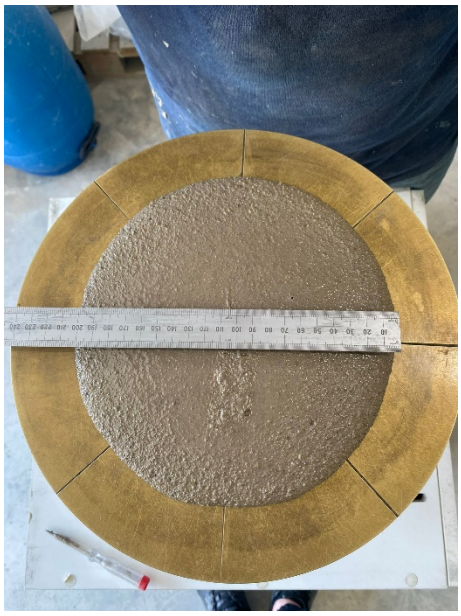


Figure 5. Mortar flow table test

Compressive strength measurements of geopolymer mortar samples after 28 days were performed according to ASTM C109 standard. Cubic samples with dimensions of 50×50×50 mm were used in the experiments. After casting, the samples were left in their molds for 24 hours, then removed from the molds and cured at room temperature (20 ± 2 °C) for 28 days. Experiments were performed on three samples for each series. The compressive strength value was determined by taking the arithmetic mean of the results obtained from the three samples. The compressive strength test is shown in Figure 6.



Figure 6. Compressive strength test (50 mm cube specimen)

Results and Discussion

Fresh State Properties

Figure 7 shows the spread values of the mixtures. The highest spread value among the mixtures was observed in the Control (C) sample, which does not contain any fibers, with 25.50 cm. The addition of sisal fibers to the geopolymer mixtures negatively affected workability and caused a significant decrease in the spread values of the mixtures. The addition of fibers to the mixtures increases internal friction within the mixture, and the network structure created by the fibers prevents the mortar from spreading freely, thus reducing workability (Wongsa et al. 2020, Lv et al. 2023, Silva et al. 2011, Lertwattanaruk et al. 2015, Silva et al. 2020).

When the effect of fiber content on processability is examined, it is observed that increasing the fiber content by volume from 0.3% to 0.6% causes a significant decrease in spreading values. While the S05-03 sample in the uncoated series showed a spread of 19.50 cm, this value decreased to 17.00 cm

in the S05-06 sample with an increase in fiber content (approximately a 13% decrease). A similar trend was observed in the graphene oxide (GO) coated series. Increasing the amount of GO-coated fibers in the mixtures resulted in a decrease in spread of approximately 15%.

This increase in fiber content reduces workability, which can be explained by the increased total fiber surface area in the mixture. Sisal fibers are hydrophilic and have a high water absorption rate. The increased surface area along with the fiber content increases the amount of water required to wet the fibers, which leads to a decrease in the amount of free water that provides fluidity to the mortar (Camargo et al. 2020, Lv et al. 2023, Qu et al. 2024, Priyadharshini et al. 2018).

When the effect of fiber coating is examined, it is seen that mortars containing graphene oxide-coated fibers provide higher workability compared to mortars with the same proportion of uncoated fibers. For example, while the spread diameter was 19.50 cm in sample S05-03, this value increased to 21.50 cm in SG05-03, resulting in a 10% increase in spread. A similar improvement was observed in samples containing 0.6% fiber. An improvement of approximately 8% in spread values was detected when transitioning from S05-06 to SG05-06. Natural sisal fibers tend to absorb mixing water due to their hydrophilic (water-loving) character. However, coating the fiber surface with GO may have reduced water absorption by clogging the pores of the fibers. Thus, the water not absorbed by the fibers increased the free water in the matrix, contributing to processability (Özen et al. 2024).

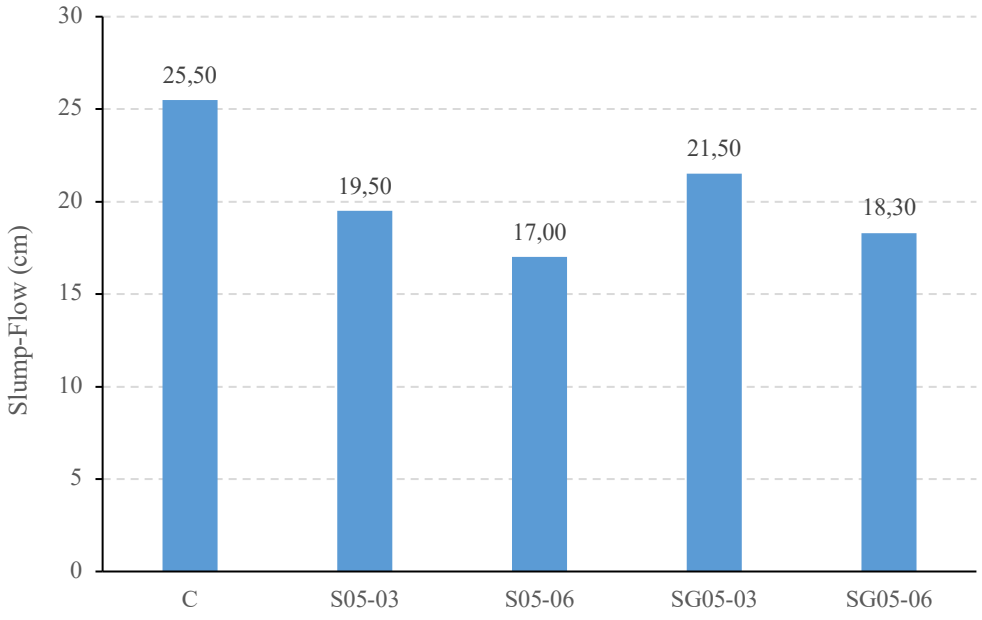


Figure 7. Flow values of the mortar mixtures

Compressive Strength

The compressive strengths of the mixtures are shown in Figure 8. As can be seen from the figure, all mixtures containing sisal fiber showed higher compressive strength than the control mixture. Samples containing untreated fiber showed a moderate improvement compared to the control, and their compressive strengths were around 35-36 MPa. In mixtures containing uncoated fiber, increasing the amount of fiber did not significantly affect the strength. A very small increase was observed. In the literature, it has been stated by Lv et al. (2022) and Moujoud et al. (2023) that natural fibers improve compressive strength to some extent. It has been stated that the uniform distribution of fibers in the matrix improves compressibility and reduces porosity in geopolymer composites (Qu et al. 2024).

A significant increase in the compressive strength of geopolimer samples containing graphene oxide-coated fibers was observed. While GO-coated samples showed an increase in strength of approximately 55-60% compared to the control sample, they also had approximately 35% higher strength than samples containing uncoated fibers. Increasing the fiber content in GO-coated samples resulted in only a slight increase in compressive strength. As seen in Figure 7, applying GO coating to sisal fibers increased the processability of geopolimer mixtures. This suggests that the fibers within the mixture are better distributed in the matrix, minimizing void formation. Furthermore, GO coating increases the adhesion of the fibers to the matrix and improves the fiber-matrix interfacial bond strength (Sarker et al. 2018, Tay et al. 2021). In this context, a positive effect of GO coating on the compressive strength of sisal fibers was determined.

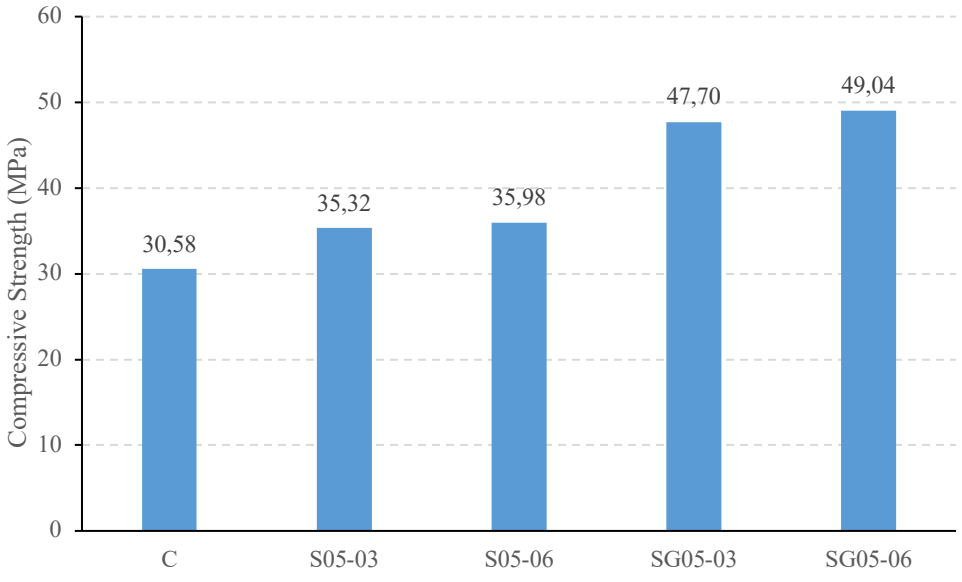


Figure 8. Compressive strength values of the mortar mixtures

Conclusions

- The incorporation of sisal fibers significantly reduced the workability of geopolymer mortars. The control mixture exhibited the highest spread value, while fiber-reinforced mixtures showed progressively lower spread values due to increased internal friction and the formation of a fiber network structure that restricted mortar flow. Increasing the fiber ratio had a significant negative impact on workability.
- The use of GO-coated sisal fibers improved workability compared to mortars containing the same proportion of uncoated fibers. The improvement in workability with GO-coated fibers is attributed to the partial reduction of water absorption by the fibers.
- The incorporation of sisal fibers positively influenced the compressive strength of geopolymer mortars. All fiber-reinforced mixtures exhibited higher strength than the control sample.
- A remarkable enhancement in compressive strength was observed in mixtures containing GO-coated sisal fibers. Increasing the fiber ratio in GO-coated mixtures led to only a minor additional strength gain, indicating that the primary improvement is associated with the surface modification rather than fiber dosage.
- The significant strength enhancement in GO-coated mixtures can be attributed to improved fiber dispersion due to increased workability, reduced void formation, and enhanced fiber–matrix interfacial bonding. The GO coating likely strengthens adhesion between the sisal fibers and the geopolymer matrix, leading to more effective stress transfer and improved load-bearing capacity.

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