

Article

The Influence of Sisal and Flax Fibers on the Mechanical Properties, Water Absorption, and Microstructure of Geopolymer Composites

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Abstract

The paradigm of sustainable development, coupled with contemporary inclinations towards green construction, exerts a considerable effect on the evolution of environmentally benign building composites. The main aim of this study is to create geopolymer composites with improved physical and mechanical properties. An examination of the properties of a geopolymer composite (GS), using ground granulated blast furnace slag (GGBFS) and plant fibers, is presented in this paper. Sisal (SF) and flax (FF) fibers, along with their combination (SF + FF), were integrated into the slag at concentrations of 0%, 0.5%, 1.0%, 1.5%, and 2% by weight. Before use, plant fibers were treated with a 5% NaOH solution. The geopolymer composites (GC) underwent evaluation for their density, compressive and flexural strengths, and water absorption characteristics. Scanning electron microscopy was employed to examine the fracture characteristics of the GC. The compressive and flexural strengths of GC were improved by including 1% SF, FF, and their combination, 0.5% SF + 0.5% FF. Compressive strength increases were 11.5%, 8.6%, and 14.5%, while flexural strength increases were 17.4%, 13%, and 19.6%, respectively. Water absorption of GC with 1% SF, FF, and SF + FF decreased by 14.6%, 10.8%, and 20.4%, respectively. The apparent synergistic performance of hybrid sisal-flax reinforcement at a total fiber content of 1% was revealed. GCs at the fracture have a homogeneous rough structure with microcracks and accumulations of geopolymer reaction products. The matrix-plant fiber interface in GC is identified by a rounded region with elongated fibers, indicating the fiber's performance under mechanical stress. The findings of this investigation suggest the feasibility of utilizing plant fibers in environmentally sound geopolymer construction composites.

Keywords: geopolymer composites; plant fibers; sisal fibers; flax fibers; compressive strength

Academic Editor: Jiabin Li

Received: 21 July 2026

Revised: 27 July 2026

Accepted: 28 July 2026

Published: 29 July 2026

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1. Introduction

The contemporary construction sector uses vast quantities of natural materials and releases significant carbon emissions, which harms the environment because of climate change and limited resources [1,2]. Traditional cement production, which is the main raw material for concrete, is accompanied by huge energy consumption and significant CO₂ emissions, which hinder sustainable development [3,4]. Compared to traditional cement concrete, geopolymer composites (GC) are a more environmentally friendly and less carbon-intensive choice. Various types of aluminosilicate components (ground granulated blast furnace slag and other types of slag, fly ash, metakaolin, microsilica), which are mainly waste or by-products, are used as a binding component for geopolymer concrete production [5–7]. In the study [8], high-strength geopolymer concretes based on ground granulated blast furnace slag (GGBFS) and fly ash (FA) were developed and subjected to high-temperature effects. Experimental studies have shown that fly ash-containing geopolymers at 100–300 °C exhibit improved durability because of secondary geopolymerization of unreacted fly ash. The combination of metakaolin with lead-zinc mine waste allows for the production of geopolymers with a compressive strength of 25–30 MPa, and the effective immobilization of toxic elements Pb, Zn, and Cd, as has been confirmed [9]. Geopolymer concretes based on slag with microsilica, reinforced with textile fibers from automobile tires, demonstrated strength increases of up to 25–30% [10]. The inclusion of 20% ceramic waste as a filler in the composition of fly ash-based geopolymer concrete had the highest strength [11]. Modification of GGBFS-based geopolymer concretes with 0.5–1% nanofibers increases the flexural strength by 15% [12]. A mixture of 60% metakaolin, 30% red mud, and 10% fly ash provides a compressive strength of 8.37 MPa after seven days [13]. Geopolymer composites of coal rock and slag, dispersion-reinforced with 0.5% basalt fiber, reach a strength of 84.05 MPa after 28 days [14]. The addition of CH₄ to metakaolin-based geopolymer effectively suppressed efflorescence and improved the transport properties of the geopolymer matrix [15]. The development of geopolymer composites has been explored in the following studies [16–19].

Improving the performance characteristics of geopolymer composites, especially their strength, is an important scientific task for expanding the scope of their application. Dispersed reinforcement of composites with different types of fibers is a well-studied and effective modification method and can significantly improve the strength and ductility of the geopolymer matrix [20–22]. Considering the principles of sustainable development, the application of renewable natural elements in the processes for manufacturing construction materials holds significant relevance. The application of plant-based fibers represents a notably promising field. Reinforcement of geopolymer concrete based on rice husk ash and fly ash with coconut fiber up to 0.2% increases its strength characteristics [23]. The impact resistance of the GC with 1% kenaf, coconut fiber, and oil palm fibers increased by 122.11%, 98.33%, and 88.33%, respectively [24]. Research indicated that incorporating 2% *Wrightia tinctoria* seed fiber (WTSF) into geopolymer composites enhanced flexural strength by 59.65%, while coconut fibers yielded a 36.55% increase in the same property [25]. Using 1% coconut fiber in geopolymers on GGBFS and sugarcane ash and with recycled aggregate improved the strength properties [26]. Dispersed reinforcement with kenaf fibers reduced the penetration depth of chlorides by approximately 20.9% [27]. An increase of 12% in the flexural strength of geopolymer concretes was observed with the inclusion of 2% hemp and sisal fibers [28]. Geopolymer matrices exhibit decreased water absorption when enhanced with keratinized hemp fiber, as reported in reference [29]. The compressive and flexural strength of geopolymer concretes reinforced with 3% sugarcane fibers increased by 16% and 35%, respectively. The inclusion of 3% sugarcane fibers in laterite-based geopolymer concretes improves their resistance to wetting-drying cycles [30]. The addition of neem fiber in an amount of up to 0.5% in geopol-

ymers based on GGBFS and fly ash can significantly improve the compressive and flexural strength [31]. Geopolymer composite deformation is augmented by the inclusion of 0.5% sisal fibers and 1.0% steel fibers [32]. Including sisal fibers in an amount of 0.25–0.75% provides an increase in the strength of the geopolymer [33]. Reinforcement of geopolymer concrete with a combination of sisal and jute fibers increases crack resistance up to 24.13% [34]. The addition of 40 mm of coconut and flax fibers increases the crack resistance of geopolymer composites by 20.65% [35]. Geopolymer concrete reinforced with flax fibers exhibits improved cracking behavior under laboratory conditions [36]. Flax tow fibers in amounts of 0.5–1% provide geopolymer matrices with the best tensile strength, thermal conductivity, and wear resistance [37].

The examination of scientific studies concerning the creation of geopolymer composites enhanced with plant fibers substantiates their potential for utilization in actual construction practices. Fiber-reinforced geopolymer composites have improved strength properties, making them suitable for the production of prefabricated structural elements, partitions, and wall panels for low-rise construction, landscaping elements, temporary industrial structures with light loads, and repair work [1,4–6]. However, the development of new geopolymer composites is accompanied by problems in the mechanism for regulating their characteristics for engineering applications [38,39]. Selecting the optimal raw material composition of the geopolymer matrix requires significant preparation, namely, a careful selection of the aluminosilicate component. The chemical and granulometric composition and other properties of the aluminosilicate components are determined; the type of alkaline activator and its optimal concentration are selected in advance. Plant fibers are inherently porous and exhibit hydrophilic properties [40,41]. They contain lignin and hemicellulose, which enter chemical reactions in the alkaline environment of the geopolymer matrix, form water-soluble compounds, and negatively affect the formation of the composite's structure. The alkaline environment destroys the molecular bonds of cellulose, reducing the strength of the fibers. Therefore, it is important to provide rational methods for recycling plant fibers to minimize potential negative effects [42–45]. This study's scientific novelty resides in the geopolymer composite development incorporating dispersed sisal and flax fibers, alongside the discovery of new experimental relationships linking composite properties and structure to reinforcement parameters. The aim of the study is to obtain geopolymer composites with improved physical and mechanical properties for the construction industry.

To achieve this goal, the research is aimed at solving the following problems:

- establishing the properties of raw materials intended for the manufacture of geopolymer composites: determining the chemical and particle size distribution of GGBFS; studying the morphology of slag particles using scanning electron microscopy (SEM) and energy-dispersive x-ray spectroscopy (EDS);
- alkaline treatment of SF and FF and calculating the optimal formulation for the geopolymer composite;
- fabrication of experimental specimens of geopolymer composites, dispersion-reinforced with SF, FF, and SF + FF, and assessment of their density, compressive strength, flexural strength, and water absorption;
- examination of the microstructural features of hardened geopolymer matrices at the matrix-plant fiber interface;
- evaluation of the effectiveness of SF, FF, and SF + FF for reinforcing a geopolymer composite based on GGBFS.

The innovative feature of this study lies in its comprehensive nature. Two types of plant fibers and a combination of them (SF, FF, and SF + FF) are used as dispersed reinforcing components. This study adds a new perspective to the scientific literature by expanding on the mechanisms by which plant fibers influence the properties of geopolymer

composites. An optimal GC composition is proposed, along with methods for preparing raw materials for GC and a manufacturing technology, enabling the integration of these findings into real-world construction practices.

2. Materials and Methods

2.1. Materials

GGBFS (Mechel, Chelyabinsk, Russia) was used as a binder for the geopolymer composite. Quartz sand (QS) (Yug-Stroy, Rostov-on-Don, Russia) and granite screenings (GS) with a grain size of 3 to 5 mm (Granit, Kamennogorsk, Russia) were used as aggregates. Table 1 details the properties of the aluminosilicate component and aggregates.

Table 1. Raw material properties.

Indicator	Actual Value
GGBFS	
Specific surface area (m ² /kg)	482
Chemical composition:	
CaO (%)	40.3
SiO ₂ (%)	37.8
Al ₂ O ₃ (%)	6.8
MgO (%)	12.1
FeO (%)	0.2
Na ₂ O (%)	1.1
K ₂ O (%)	0.9
TiO ₂ (%)	0.1
MnO (%)	0.5
S (%)	0.2
QS	
Bulk density (kg/m ³)	1335
Apparent density (kg/m ³)	2598
The content of dust and clay particles (%)	0.11
GS	
Bulk density (kg/m ³)	1427
Apparent density (kg/m ³)	2661
Resistance to fragmentation (wt %)	11.5
The content of lamellar and acicular grains (wt %)	7.3

As depicted in Figure 1, the particle distributions for GGBFS and QS are displayed.

The particle size distribution curve presented in Figure 1a demonstrates that a majority of GGBFS particles (84.4%) are found in the size interval of 0.2 µm to 36 µm. The remaining particulate matter measures between 36 micrometers and 97 micrometers. As illustrated in Figure 1b, the quartz sand exhibits a fineness modulus of 1.69.

The results of SEM and EDS analysis of GGBFS particles are presented in Figures 2 and 3.

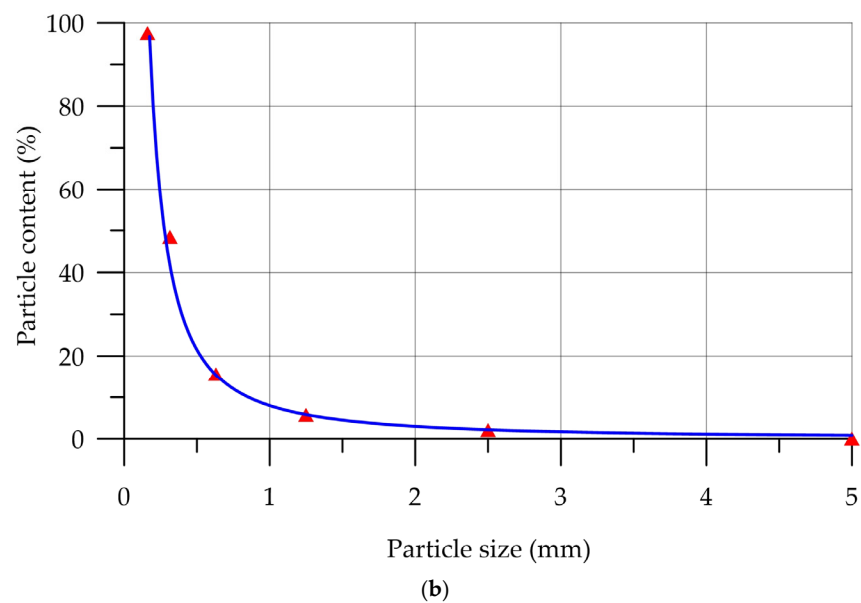
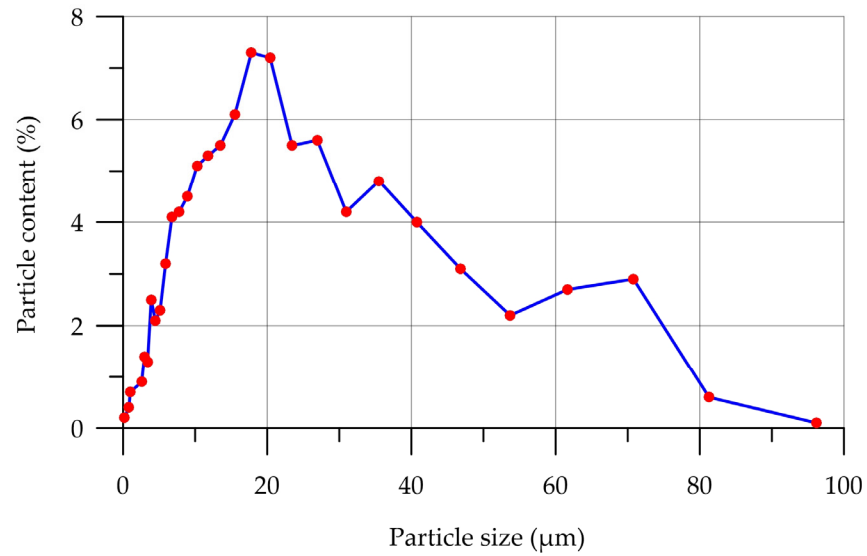


Figure 1. Particle distributions: (a) GGBFS; (b) QS.

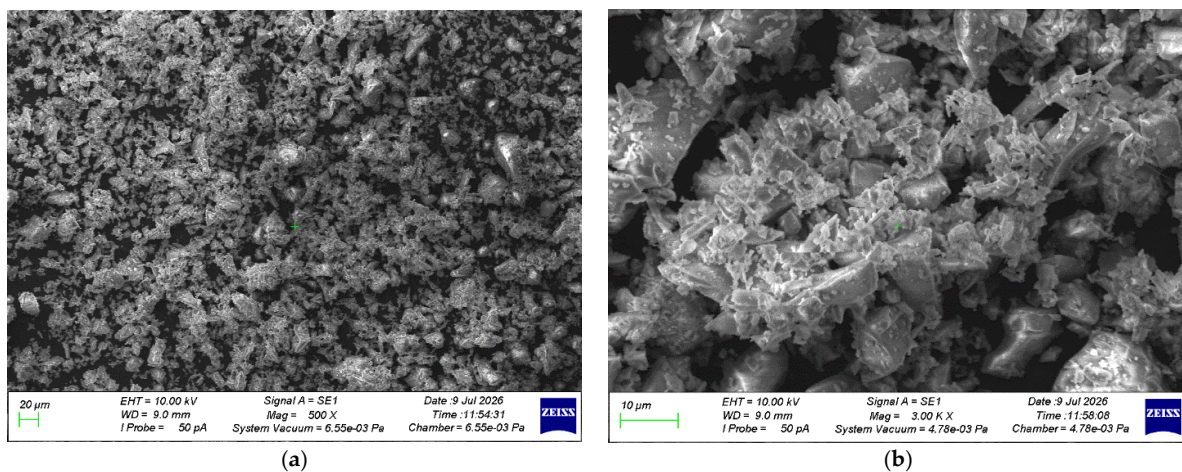


Figure 2. SEM image of GGBFS: (a) at 500× magnification; (b) at 3000× magnification.

GGBFS particles have an irregular shape. Surface observations reveal that larger particles have accumulated smaller particle clusters.

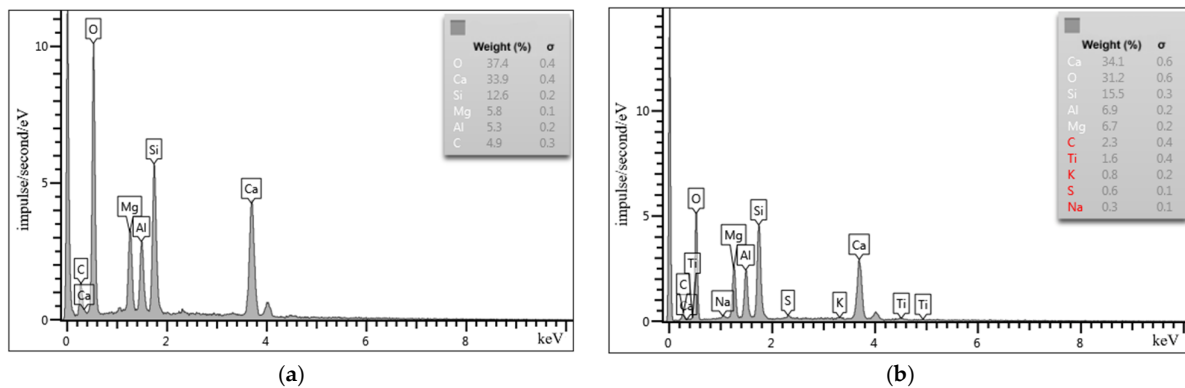


Figure 3. EDS of GGBFS particles: (a) spectrum 1; (b) spectrum 2.

EDS analysis of GGBFS revealed the presence of the following chemical elements: Ca; O; Si; Al; Mg; C; Ti; K; S; Na. Figure 3 illustrates the mass fractions of each chemical element.

Sodium hydroxide (NaOH) solution with a concentration of 8 M and sodium liquid glass ($\text{Na}_2\text{O}(\text{SiO}_2)_n$) (Kerami-NSK, Novosibirsk, Russia) were used as alkaline activators. Table 2 delineates the characteristics of the alkaline activators.

Table 2. Characteristics of alkaline activators.

Indicator	Actual Value
NaOH	
Sodium hydroxide content (%)	99.1
Sodium carbonate content (%)	0.26
Sodium chloride content (%)	0.032
$\text{Na}_2\text{O}(\text{SiO}_2)_n$	
Mass fraction of silicon dioxide (%)	29.63
Iron oxide and aluminum oxide content (%)	0.04
Sodium oxide content (%)	9.65
Silicate modulus	3.0
Density (g/cm^3)	1.41

The plasticizing additive Polyplast Linamix PC (P) (Polyplast, Novomoskovsk, Russia) was also used. Properties: pH—5; density— $1.03 \text{ g}/\text{cm}^3$.

Dispersed reinforcement was achieved through the utilization of sisal fibers (SF) and flax fibers (FF). The characteristics of the plant fibers are detailed in Table 3. The cutting of plant fibers was carried out manually in laboratory conditions with control of the length of the dies in a given range from 10 to 25 mm. The optimal length of plant fibers was determined in advance during preliminary experiments. The visual presentation of the plant fibers is illustrated in Figure 4.

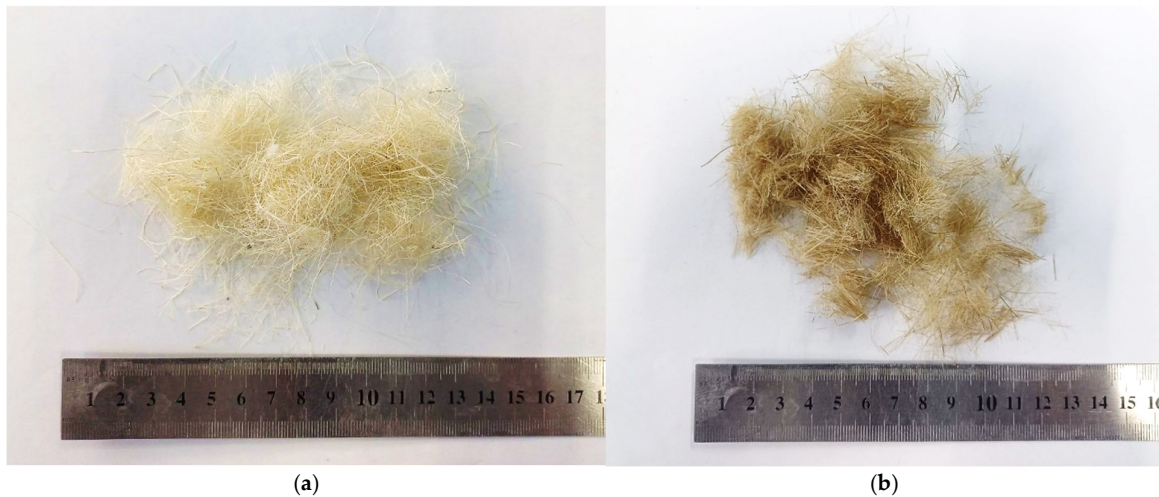


Figure 4. Plant fibers: (a) SF; (b) FF.

Table 3. Features of fibrous plant materials.

Fiber Type	Fiber Length (mm)	Fiber Density (g/cm ³)	Tensile Strength (MPa)
SF	10–25	1.49	410–450
FF		1.17	370–400

2.2. Methods

The compositions of GS with various dosages of plant fibers are shown in Table 4. Sisal fibers, flax fibers, and a combination of these were used in amounts of 0%, 0.5%, 1.0%, 1.5%, and 2% of the GGBFS mass.

Table 4. Geopolymer composite compositions with consumption per 1 m³.

Mixture Type	GGBFS (kg)	QS (kg)	GS (kg)	NaOH/8M (L)	Na ₂ O(SiO ₂) _n (L)	SF (kg)	FF (kg)	SF + FF (kg)
0SF/0FF	405	550	1295	80	80	0	0	0
0.5SF/0FF	405	550	1295	80	80	2.0	–	–
1.0SF/0FF	405	550	1295	80	80	4.1	–	–
1.5SF/0FF	405	550	1295	80	80	6.1	–	–
2.0SF/0FF	405	550	1295	80	80	8.1	–	–
0SF/0.5FF	405	550	1295	80	80	–	2.0	–
0SF/1.0FF	405	550	1295	80	80	–	4.1	–
0SF/1.5FF	405	550	1295	80	80	–	6.1	–
0SF/2.0FF	405	550	1295	80	80	–	8.1	–
0.25SF/0.25FF	405	550	1295	80	80	–	–	2.0
0.5SF/0.5FF	405	550	1295	80	80	–	–	4.1
0.75SF/0.75FF	405	550	1295	80	80	–	–	6.1
1.0SF/1.0FF	405	550	1295	80	80	–	–	8.1

p—for all types of mixtures.

Experimental geopolymer composite samples were manufactured in laboratory conditions using the following steps: Step 1—Dosing of all raw materials (GGBFS, GS, and QS) according to the formulation; Step 2—Plant fibers were treated with an alkaline solution (5% NaOH) before use to improve the adhesion of the fiber to the matrix. First, plant fibers were cut into pieces of a given length from 10 to 25 mm. Then, the 5% NaOH solution was prepared. The ratio of fibers to solution was 1:10. The prepared plant fibers were

soaked in 5% NaOH solution for 1 h. After an hour, the fibers were removed from the solution, washed, and kept in water for 12 h to remove residual alkali and dissolved impurities. To minimize moisture, the treated fibers were subsequently dried in an oven at 60–70 °C for 24 h. After drying, the fibers were conditioned; Step 3—Preparation and dosing of alkaline activators. NaOH with a molarity of 8 M was prepared 24 h before use. Sodium water glass and plasticizer were dosed in the required quantities; Step 4—The GGBFS, GS, and QS were added in their dry form to a laboratory mixer and processed for 60 s; Step 5—The dry mixture of raw components was supplemented with alkaline activator solutions and a plasticizing additive. This mixture was thoroughly blended until a uniform texture was achieved. Following this, plant fibers were introduced, and the geopolymer mixture was subjected to further agitation; Step 6—The completed geopolymer composition was deposited into molds via a three-step process. In every phase, the metal matrices holding the admixture were compressed upon a laboratory vibration device; Step 7—Geopolymer specimens underwent a 28-day curing period within a standard curing chamber, maintained at a temperature of 20 ± 2 °C and a relative humidity of $95 \pm 5\%$.

Figure 5 outlines the comprehensive experimental approach.

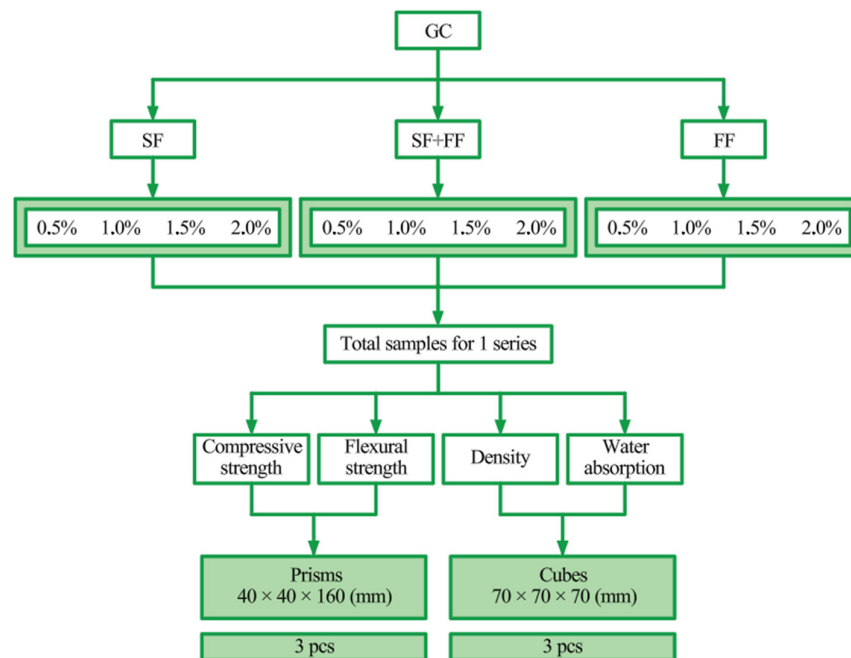


Figure 5. Experimental design.

A total of 39 prism specimens and 39 cube specimens were prepared. The total number of experimental compositions was 13. To assess the density, compressive strength, bending strength, and water absorption of GC, for each composition, three cube samples were made, from which the density was first determined, and then water absorption; and three prism samples were made, from which the bending strength was first determined, and then, on the six resulting half-prisms, the bending strength was determined. Thus, to determine compressive strength, 78 half-prisms out of 39 prism specimens were used; bending strength—39 prism specimens; density and water absorption—39 cubic specimens.

The density of geopolymers with plant fibers was determined using cube specimens measuring 70 × 70 × 70 mm according to method [46]. The volume of the experimental specimens was determined based on their geometric parameters, measured with calipers. The mass of the specimens was determined using a laboratory scale. Density was calcu-

lated using Equation (1) and rounded to 1 kg/m³. A series of specimen densities was computed through the calculation of the arithmetic mean derived from triplicate test results. It is important that the density values differ from each other by no more than 20%.

$$\rho_w = \frac{m}{V} \cdot 1000 \quad (1)$$

here, m is the sample mass (g), and V is the sample volume (cm³).

The compressive (CS) and flexural strengths (FS) of geopolymer specimens with plant fibers were determined on 40 × 40 × 160 mm prism specimens using the method described in [47]. The prism specimens were initially mounted on supports that were mounted on a special device. The span between the supports was recorded as 100 mm, with an allowable deviation of ±0.2 mm. A load was applied at a rate of 50 ± 10 N/s. Equation (2) was employed to ascertain the flexural strength, demonstrating an accuracy of 0.1 MPa. The test's result was calculated by computing the arithmetic mean of the two largest values:

$$R_{tb} = 0.00234 \cdot F \quad (2)$$

here, F is the ultimate load (N).

After determining the flexural strength, six half-specimens were subjected to compression tests. Initially, a half-specimen was mounted between two metal plates with an area of 2500 mm². The load was applied to the specimens at a rate of 2.0 ± 0.5 MPa/s. Equation (3) was employed to compute the CS, resulting in an accuracy of 0.1 MPa:

$$R = \frac{F}{S} \quad (3)$$

here, F is the breaking load (N), and S is the plate's working surface area (mm²).

Figures 6 and 7 illustrate the determination of CS and FS of GC reinforced with plant fibers.

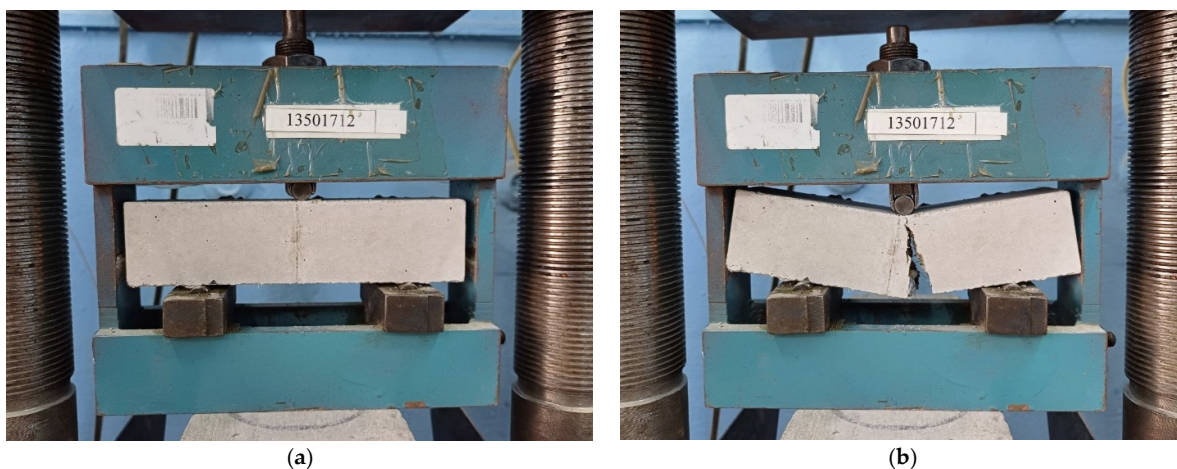


Figure 6. Testing of prism specimens for bending strength GC: (a) before failure; (b) after failure.



Figure 7. CS testing of half-specimens (GC): (a) before failure; (b) after failure.

The water absorption of GC was ascertained by employing the procedure detailed in [48]. The specimens were first situated in a water-filled receptacle, with the water level maintained at 50 mm above the specimen's uppermost point. Following a 24-h saturation, the specimens were subjected to weighing. The process of saturation and weighing was iterated until the discrepancy between results did not exceed 0.1%. The calculation of water absorption utilized Equation (4) and yielded a result with 0.1% accuracy. Calculation of the arithmetic mean of all series values served as the determinant for the test result:

$$W = \frac{m_w - m_d}{m_d} \cdot 100 \quad (4)$$

here, m_w is the mass of the water-saturated sample (g), and m_d is the mass of the dry sample (g).

The microstructure of the dispersion-reinforced geopolymers was assessed using a ZEISS CrossBeam 340 scanning electron microscope (Carl Zeiss Microscopy GmbH, Jena, Germany) equipped with an Oxford Instruments X-Max 80 X-ray microanalyzer (Oxford Instruments, Abingdon, England).

A one-way analysis of variance (ANOVA) was performed on the data sets of geopolymer composite properties (density, compressive strength, flexural strength, and water absorption). This included the calculation of sums of squares, mean squares, degrees of freedom, and F and p -values. A p -value is considered statistically significant if $p < 0.05$. For each property, three experimental groups were analyzed separately depending on the fiber type: SF, FF; SF + FF. Five experimental groups were also analyzed separately depending on the percentage of plant fiber.

3. Results and Discussion

The density (ρ_w) of GC, dispersedly reinforced with plant fibers SF, FF, and SF + FF in different dosages, is presented in Figure 8.

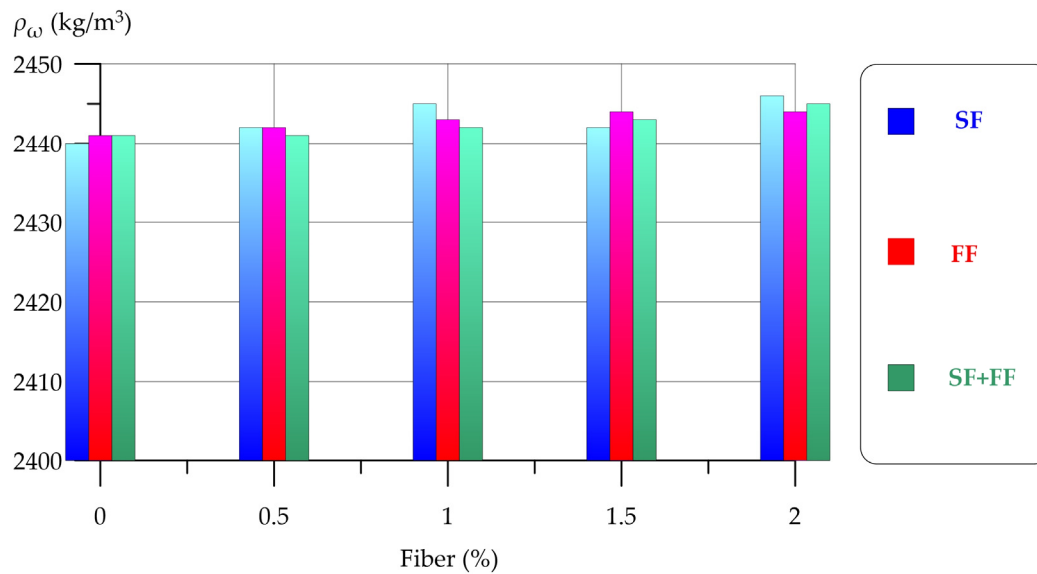


Figure 8. Density (ρ_w) of GC versus plant fiber content.

The density of geopolymer composites reinforced with SF at applications ranging from 0.5% to 2.0% varied from 2440 kg/m³ to 2446 kg/m³. The density values observed for FF composites were between 2441 kg/m³ and 2444 kg/m³. A variation in density, from 2441 kg/m³ to 2445 kg/m³, was observed in geopolymer composites reinforced by a composite of SF and FF fibers. Consequently, the dispersion of GC with various plant fibers within the observed ranges had no substantial impact on the composite's density.

The analysis of variance (ANOVA) of the density determination data for geopolymer composites reinforced with SF, FF, and SF and FF is presented in Table 5. Its results confirm the conclusion that the factors under consideration have little effect on the density of GC.

Table 5. Analysis of variance of the GC density determination data.

	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Stat	<i>p</i> -Value
Fiber type					
Between Groups	2	0.9333	0.4667	0.1333	0.8765
Within Groups	12	41.999	3.5		
Total:	14	42.932			
Fiber dosage					
Between Groups	4	32.9326	8.2331	8.2331	0.0033
Within Groups	10	10.0001	1		
Total:	14	42.9327			

Figure 9 illustrates the findings from the analysis of CS (R) in GC composites containing SF, FF, and SF + FF plant fibers. Figures 9–11 show error bars that indicate the confidence interval within which the true value of the parameter lies with a 95% confidence level.

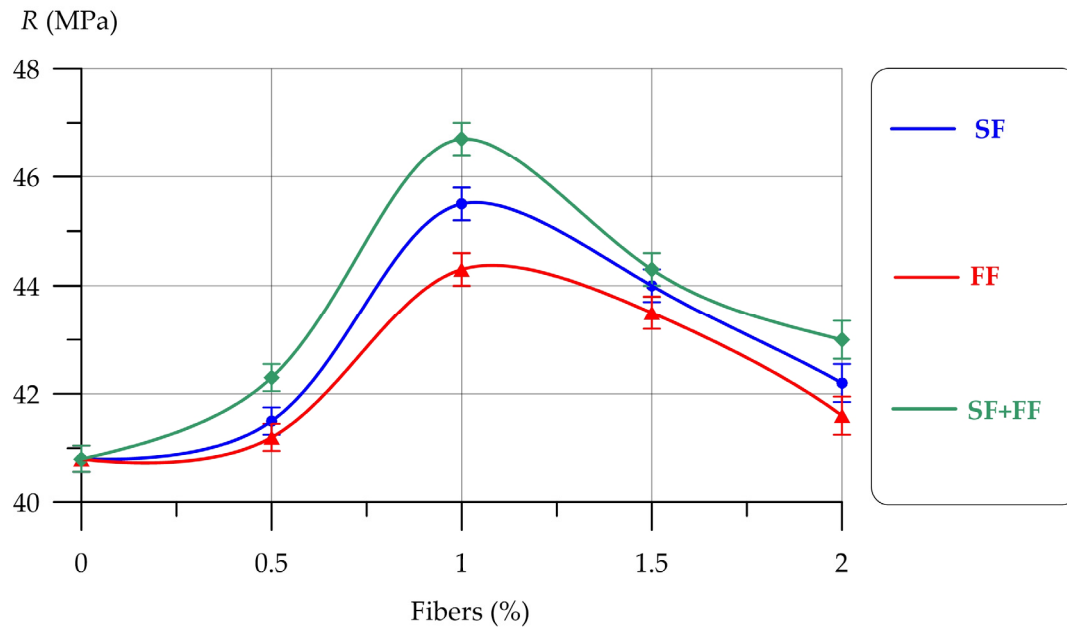


Figure 9. CS (R) of GC as a function of plant fiber content.

Including SF, FF, and SF + FF in the ranges from 0.5% to 2.0% increases the CS of GC. Maximum compressive strengths of 45.5 MPa, 44.3 MPa, and 46.7 MPa were recorded for GC compositions of types 1.0SF/0FF, 0SF/1.0FF, and 0.5SF/0.5FF containing 1% plant fibers. Further, with an increase in fiber content to 2%, the reinforcement efficiency decreases. The increases in compressive strength for GC with an optimal total plant fiber content of 1% were 11.5%, 8.6%, and 14.5%, respectively. For GC compositions of types 2.0SF/0FF, 0SF/2.0FF and 1.0SF/1.0FF, the increases in compressive strength were 3.4%, 2.0%, 5.4%, respectively. The error bars shown in Figure 9 range from ± 0.2 to ± 0.6 MPa. Table 6 displays the analysis of variance (ANOVA) for the CS determination results of GC with SF, FF, and SF + FF.

Table 6. Analysis of variance for the results of determining the CS of GC.

	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Stat	p-Value
Fiber type					
Between Groups	2	3.2573	1.6287	0.4442	0.6514
Within Groups	12	43.9949	3.6662		
Total:	14	47.2523			
Fiber dosage					
Between Groups	4	42.4128	10.6032	21.9077	0.0001
Within Groups	10	4.8399	0.484		
Total:	14	47.2527			

It was found that among the studied dispersed reinforcement options, the SF + FF combination was the most effective compared to SF and FF reinforcement alone. When comparing SF and FF, GC with SF demonstrated the greatest strength gains. The p -value < 0.05 is statistically significant for such a factor as the dosage of plant fiber and insignificant for the factor reflecting the type of fiber. Accordingly, the dosage of plant fibers has a greater effect on the compressive strength.

Figure 10 shows the flexural strength (R_{bt}) results for GC, SF, FF, and SF + FF dispersed plant fiber-reinforced GC.

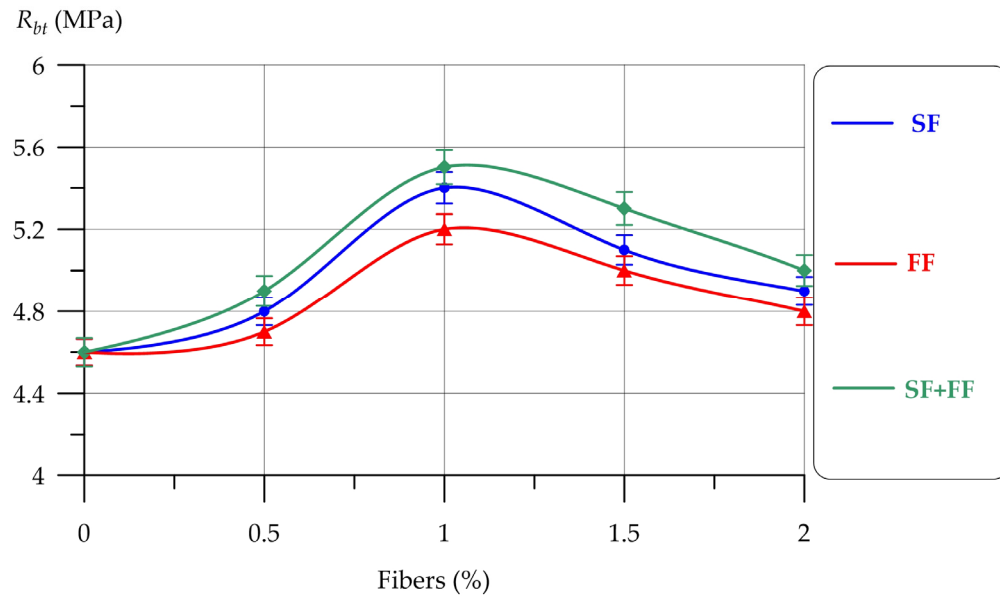


Figure 10. Flexural strength (R_{bt}) of GC as a function of plant fiber content.

FS of GC increases with dispersed plant fiber reinforcement. The highest bending strength of 5.4 MPa, 5.2 MPa, and 5.5 MPa was recorded for compositions of types 1.0SF/0FF, 0SF/1.0FF, and 0.5SF/0.5FF. The increases in flexural strength were 17.4%, 13.0%, and 19.6%, respectively. Further, with an increase in plant fiber content to 1.5% and 2%, the increases in FS decrease. For GC compositions of types 2.0SF/0FF, 0SF/2.0FF, and 1.0SF/1.0FF, the increases in flexural strength were 6.5%, 4.3%, and 8.7%, respectively. The inclusion of plant fibers in optimal dosages allows for the most effective redistribution of tensile stresses, which under bending loads are concentrated in the lower zone of the geopolymer matrix, preventing the development of cracks, which significantly affects the strength of fiber-reinforced composites. In addition, factors such as the type of fiber used, matrix material, fiber percentage, fiber arrangement in the matrix, and production method have a significant impact on the strength of dispersion-reinforced composites. The error bars shown in Figure 10 are ± 0.1 MPa. The variance analysis of the flexural strength data for GC reinforced with SF, FF, and SF + FF is presented in Table 7.

Table 7. Variance analysis of the flexural strength data for GC.

	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Stat	p-Value
Fiber type					
Between Groups	2	0.1	0.05	0.5474	0.5922
Within Groups	12	1.096	0.0913		
Total:	14	1.196			
Fiber dosage					
Between Groups	4	1.0627	0.2657	19.9172	0.0001
Within Groups	10	0.1334	0.0133		
Total:	14	1.1961			

Based on the results of experimental studies, it was found that the content of plant fibers has the greatest effect on flexural strength compared to the type of fiber.

The results of water absorption (W) determination for GCs dispersed with plant fibers are presented in Figure 11.

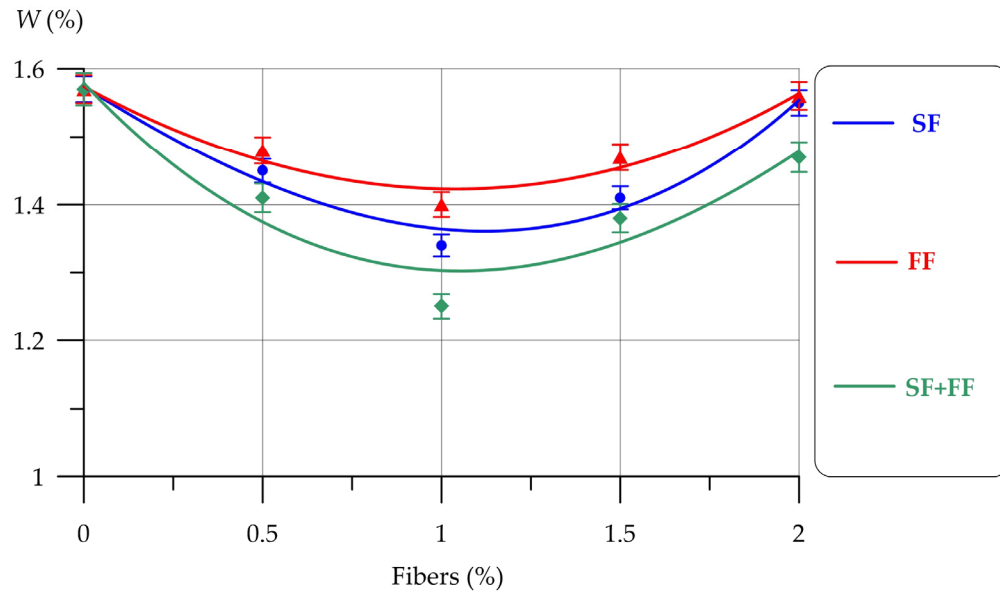


Figure 11. Water absorption (W) of GC as a function of plant fiber content.

As revealed in Figure 11, the incorporation of SF, FF, and SF + FF plant fibers at their optimal concentrations effectively minimizes water absorption. The water absorption of GC compositions of types 1.0SF/0FF, 0SF/1.0FF, and 0.5SF/0.5FF was the lowest and amounted to 1.34%, 1.40%, and 1.25%, which is lower than the control value by 14.6%, 10.8%, and 20.4%, respectively. The error bars shown in Figure 11 are $\pm 0.05\%$. Inclusion of 1.5% and 2% plant fibers was less effective, and at 2%, the water absorption of the composites was comparable to the control value. Plant fibers in the GC structure, at an optimal dosage of up to 1%, can reduce water absorption through the following mechanisms. Fibers in the geopolymer matrix structure promote void redistribution and the formation of a more homogeneous structure by distributing the solid phase in the fresh geopolymer mixture and reducing segregation. Plant fibers can also partially block capillary channels, which impedes water migration. The increase in water absorption at fiber content above 1% is explained by the fact that the fibers agglomerate, creating voids in the GC structure that are filled with water during the saturation of the composite. Furthermore, at the phase boundaries in these zones, the plant fibers are insufficiently coated by the geopolymer matrix, creating free spaces that facilitate water access. An analysis of variance (ANOVA) for the GC water absorption results is given in Table 8.

Table 8. Analysis of variance (ANOVA) for the GC water absorption results.

	Degrees of Freedom (DF)	Sum of Squares (SS)	Mean Square (MS)	F-Stat	p-Value
Fiber type					
Between Groups	2	0.0162	0.0081	0.8661	0.4453
Within Groups	12	0.1123	0.0094		
Total:	14	0.1285			
Fiber dosage					
Between Groups	4	0.1057	0.0264	11.5235	0.0009
Within Groups	10	0.0229	0.0023		
Total:	14	0.1286			

As with strength properties, plant fiber content has a greater impact on water absorption reduction than fiber type.

The microstructural characteristics of the GC control composition and composites reinforced with SF, FF, and SF + FF were examined. Morphological images of the structure of geopolymer composites with compositions of 0SF/0FF, 1.0SF/0FF, 0SF/1.0FF, and 0.5SF/0.5FF are presented in Figures 12–15.

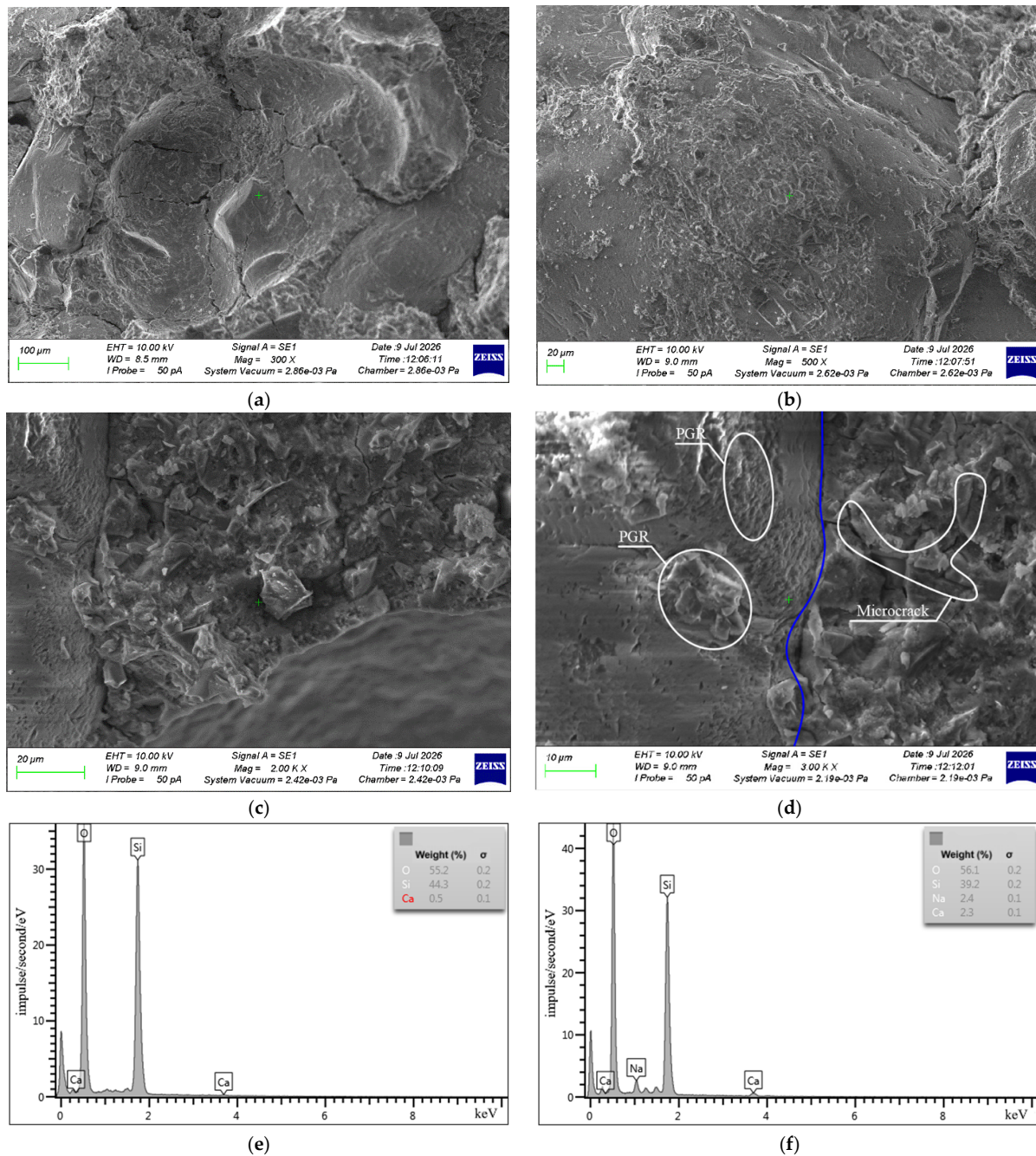


Figure 12. Images of the GC structure of the 0SF/0FF control composition with magnification: (a) 300x; (b) 500x; (c) 2000x; (d) 3000x; (e) spectrum 1; (f) spectrum 2.

Figure 12 illustrates the microstructural characteristics of the GGBFS-based geopolymer composite, which was activated with sodium hydroxide solution and liquid sodium silicate, following a 28-day curing period. The hydration products are mainly represented by gel systems: C-S-H (calcium silicate hydrate); C-A-S-H (calcium aluminum silicate hydrate); N-A-S-H (sodium aluminosilicate hydrate) [49,50]. These gel systems are the main

binding components and determine the future strength properties of the geopolymer matrix. Multiple clusters of products of geopolymer reactions (PGR) are observed on the surface of the filler grains. The fracture structure is rough. Clear phase boundaries are visible between the geopolymer binder and the aggregate grains. Microcracks are present in the GC structure.

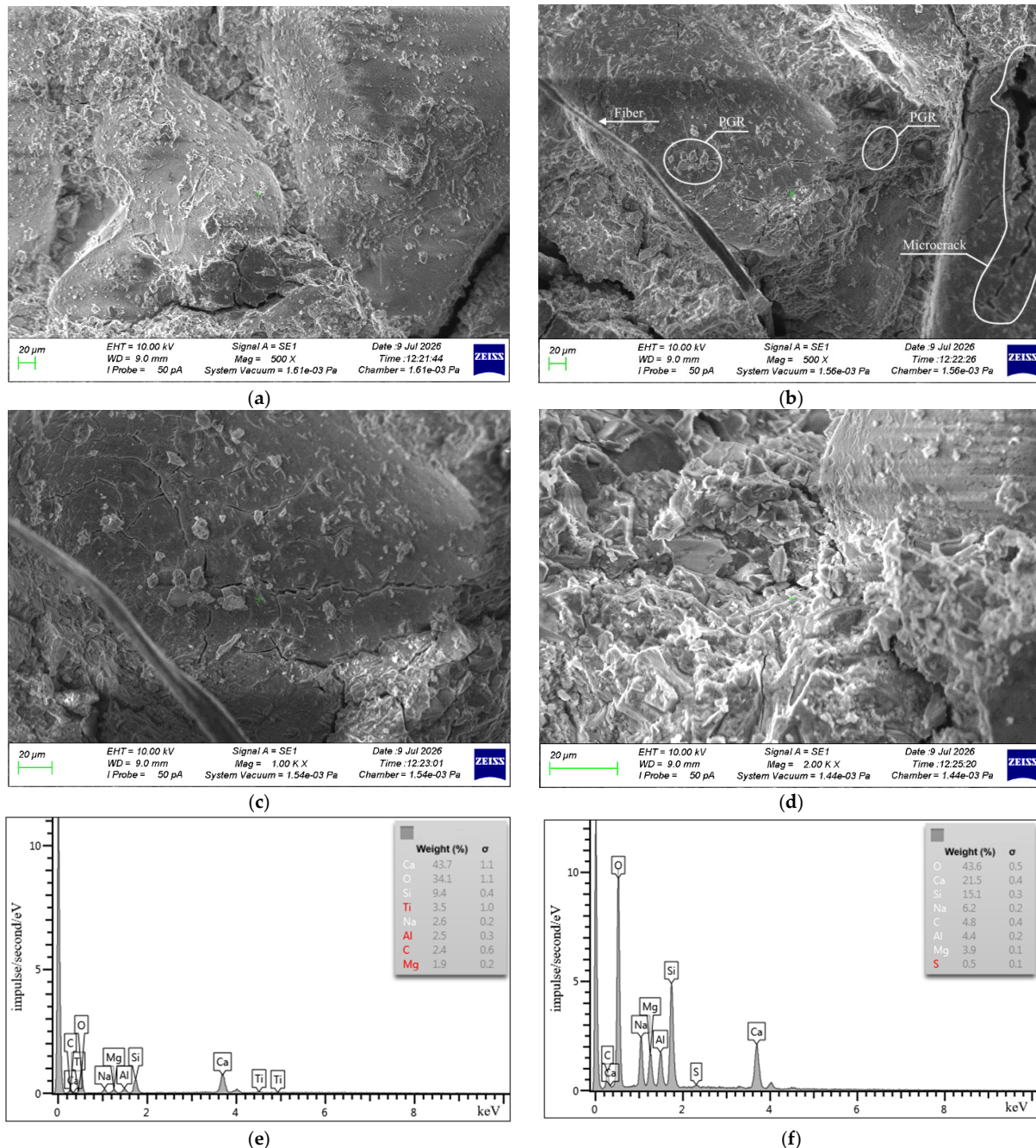


Figure 13. Images of the GC structure of the 1.0SF/0FF type composition with magnification: (a) 500x; (b) 500x (with markings); (c) 1000x; (d) 2000x; (e) spectrum 1; (f) spectrum 2.

The transverse fracture surface morphology of sisal fiber-dispersedly reinforced GC exhibits similarity. On the surface of aggregate grains, multiple zones of accumulation of geopolymerization reaction products are observed. The “matrix-plant fiber” phase boundary is represented by a clear rounded area with plant fiber extended from it, which

indicates the operation of the fiber in the process of mechanical action on the composite. Roughness and microcracks are observed on the fracture surface of the composite.

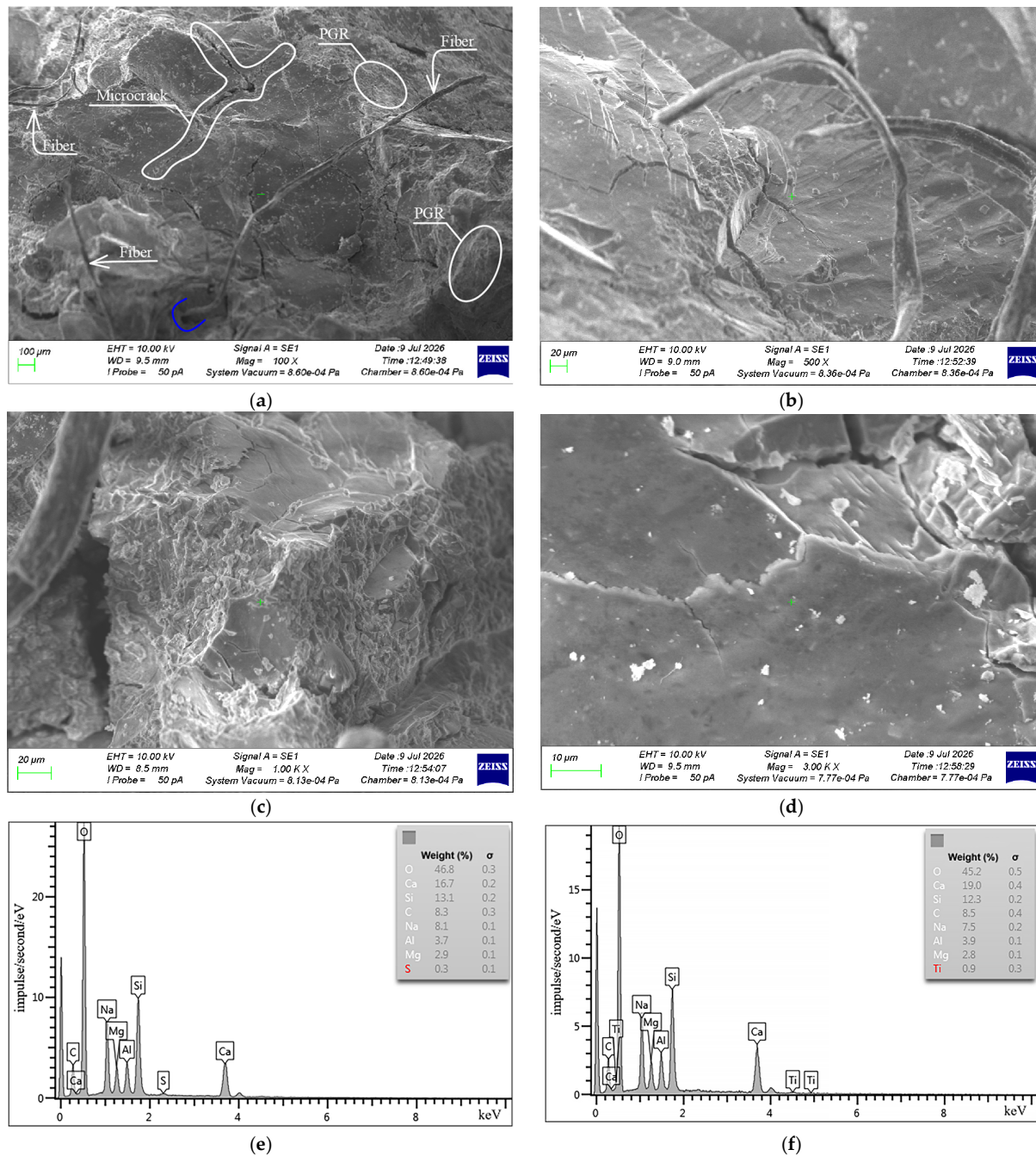


Figure 14. SEM images of the GC structure of the 0SF/1.0FF composition with magnifications of: (a) 100 $\times$; (b) 500 $\times$; (c) 1000 $\times$; (d) 3000 $\times$; (e) spectrum 1; (f) spectrum 2.

The matrix-plant fiber interface of the GC reinforced with flax fiber is also represented by a rounded region with an elongated fiber, indicating the fiber's performance under mechanical stress. Small accumulations of geopolymerization reaction products are observed on the surface of the plant fibers. A network of microcracks is observed.

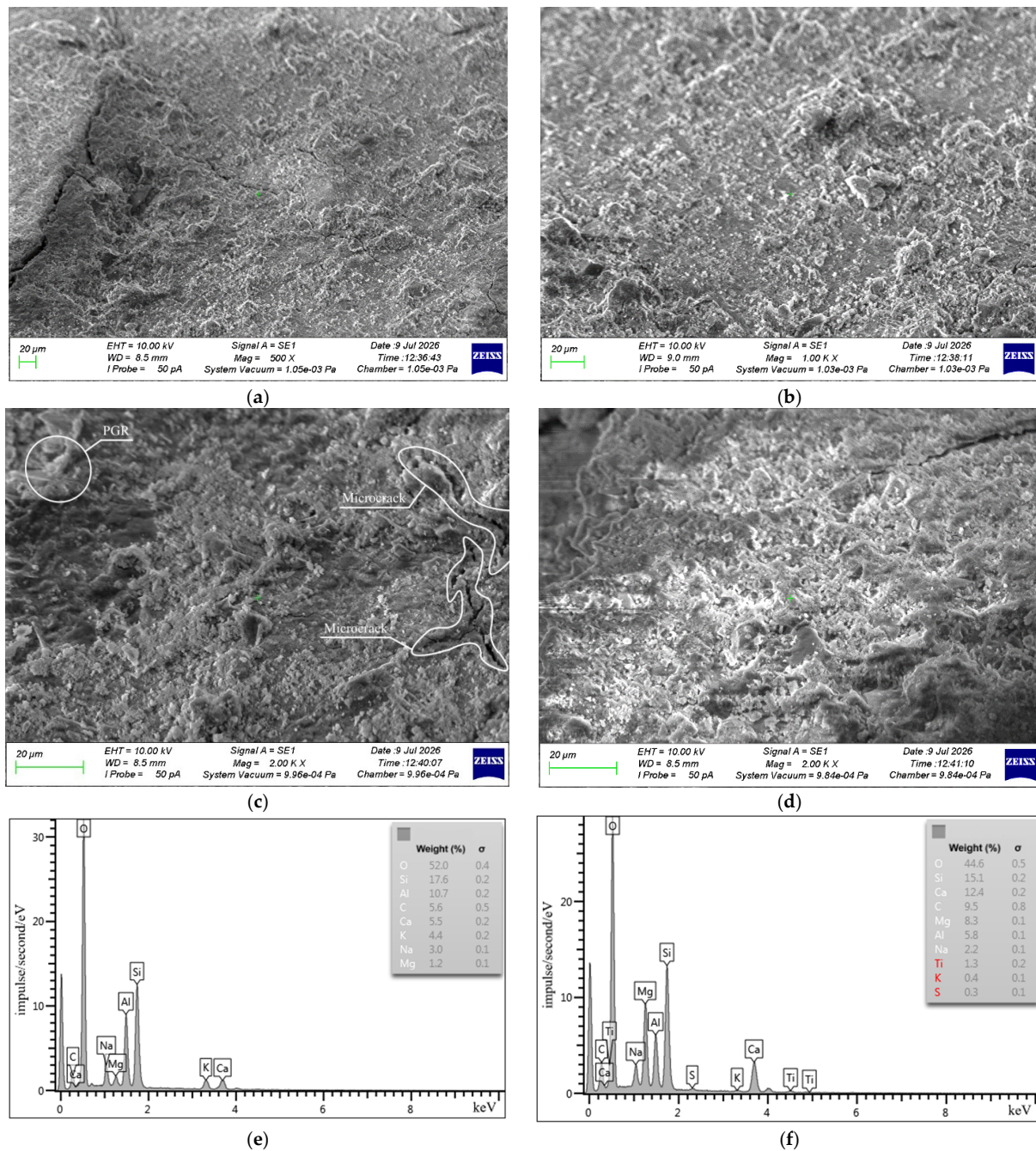


Figure 15. Images of the GC structure of the 0.5SF/0.5FF type with magnification: (a) 500×; (b) 1000×; (c) 2000× (with markings); (d) 2000×; (e) spectrum 1; (f) spectrum 2.

The structure of GC with 0.5% sisal fibers and 0.5% flax fibers is homogeneous. Large clusters of geopolymerization reaction products on the transverse fracture surface indicate strong interphase bonds between the GC components. The performed microscopic study confirms the mechanism of interaction between plant fibers and the geopolymer matrix. The failure mechanism of reinforced GC is accompanied by crack bridging, fiber pullout from the geopolymer matrix, and fiber rupture. Fibers in GC act as crack-bridging agents, reducing microcrack formation and increasing load transfer efficiency [51]. EDS analysis of GC identified O, Ca, Si, and Al, confirming the presence of the main components characteristic of a geopolymer binder in the material's structure.

Dispersed reinforcement of GC with SF, FF, and SF + FF plant fibers in optimal dosages improves the composite's properties through the following main mechanisms:

- redistribution of internal stresses in the GC structure: plant fibers, being in the geopolymer matrix, participate in the uniform distribution of internal stresses that arise in the GC structure due to shrinkage processes in the early stages of hardening; with a more uniform distribution of internal stresses, the number of microcracks and defects in the geopolymer matrix decreases [52];
- prevention of the development of cracks and defects in the structure under the influence of mechanical loads: randomly located fibers of plant fiber, being in the crack development zone, are included in the work and absorb part of the tensile forces;
- when compressive and bending mechanical loads are applied to GC, part of the load is transferred through tangential forces at the phase boundaries, known as the “plant fiber matrix”, that is, the fibers smooth out stress peaks in weak structural zones of the matrix and distribute them more evenly throughout the matrix structure [53];
- plant fibers are characterized by a rough structure with pronounced irregularities; during the process of strength gain, geopolymerization reaction products accumulate in these zones and contribute to the formation of stronger bonds at the interface between the matrix and plant fiber phases, which subsequently directly affects the strength and deformation properties of the composite.

Dispersed reinforcement of GC with a combination of sisal and flax fibers is more effective than reinforcement with these fibers individually due to the following factors:

- differences in tensile strength: SF and FF have different tensile strengths, which allows for the redistribution of bending mechanical loads over a wider range;
- differences in density and morphology: SF and FF have different density and morphology; the sisal fibers used in this study are characterized by a higher density; the surface of sisal fibers is rough with pronounced irregularities; the surface of flax fibers is smoother, also containing irregularities; due to these differences, SF and FF can work more effectively in the geopolymer matrix at the microlevel, delaying the development of microcracks, and at the macrolevel, blocking the development of larger cracks;
- potential complementary behavior in crack bridging: SF and FF react differently to the occurrence of cracks at the initial stages of their appearance and, together, more effectively inhibit the development of cracks at the micro and macro levels in the GC structure.

The content of plant fibers in amounts up to 1% is the most effective and provides maximum increases in strength properties. Maximum increases in compressive and flexural strength of 14.5% and 19.6% have GC compositions of type 0.5SF/0.5FF. SF, FF, and SF + FF are uniformly distributed throughout the geopolymer matrix. The fiber orientation is random, which is a positive factor. This random fiber distribution allows for more efficient stress redistribution within the geopolymer matrix.

Improved performance properties of geopolymer composites due to dispersed reinforcement with plant fibers are also confirmed by studies by other authors (Table 9).

Table 9. Comparative analysis of the effect of plant fibers on composite properties.

Reference	Fiber Type	Optimal Percentage of Reinforcement	Results Achieved
[28]	Hemp Fiber + Sisal Fiber	1.0% + 1.0%	Compressive strength increased by 9%, tensile strength by 4.8%, and flexural strength by 19%
[25]	Wrightia Tinctoria Seed Fiber	2.0%	Mechanical and microstructural properties of geopolymer composites were improved

[54]	Coconut Fiber Cellulose	0.8%	The splitting tensile strength and flexural strength of slag- and fly ash-based composites increased by 35.7% and 33.3%, respectively
[55]	Sisal, Jute, Coconut, and Flax Fibers	0.5%	An increase in strength properties of geopolymer concrete was recorded
[56]	Coconut Fiber	0.25%	The geopolymer composite demonstrated improved strength properties and excellent resistance to acidic and sulfate-rich environments
[57]	Sisal Fiber	2.0%	Sodium bicarbonate-treated sisal fibers were found to increase the flexural strength of the geopolymer matrix by 82%
[58]	Flax Fiber	1.0%	An optimal geopolymer mixture for soil stabilization was obtained from slurry activated with 12 M NaOH and flax fiber
[59]	Flax Fiber	1.0%	An increase in the strength of the geopolymer composites of up to 35% was recorded
[60]	Flax Fiber	0.15–0.50%	A 27% reduction in autogenous shrinkage and an increase in tensile strength of high-strength concrete were recorded
[61]	Sisal Fiber	2%	A composition of geopolymer plaster reinforced with sisal fiber has been developed as a strengthening material for stone structures
[62]	Coconut Fiber	1%	Acid-resistant geopolymer solutions with improved strength were obtained from brick waste and coconut fibers

The comparative analysis indicates that incorporating plant fibers into GC at optimal concentrations, ranging from 0.15% to 2%, enhances its physical and mechanical characteristics, leading to increased compressive and flexural strength while reducing shrinkage [26,58]. However, it is important to note that the improvements in the GC properties reflected in Table 9 also depend on other formulation and technological factors, which in most cases are individual for each type of GC, namely the type of aluminosilicate component, the type and concentration of the alkaline activator, the length of the reinforcing plant fibers and the method of their processing, the conditions for curing the composites (humidity and temperature conditions) [25,28,54–62].

In this study, sisal and flax fibers and their combination in an amount of 1% improve the strength properties of geopolymer composites, which correlates well with the purpose of the study. GC has a homogeneous, well-organized matrix with a smaller number of microstructural defects. It should be noted that reinforcement with SF, FF, and SF + FF in dosages greater than 1% is impractical, since the efficiency of the fibers in the matrix decreases. The so-called effect of supersaturation of the GC matrix with plant fibers occurs. The fibers cannot be evenly distributed throughout the structure; they tangle and form weak zones [63–66]. In recent years, plant fiber-reinforced building materials have many advantages over traditional building materials and have attracted attention, especially in terms of durability, environmental friendliness, and sustainability [67–69]. The developed GCs have important environmental and practical significance.

The use of industrial by-products such as GGBFS as a binder component and the integration of renewable plant fibers into geopolymer composites align with key sustainable development principles aimed at reducing carbon footprints and energy consumption. These composites are an excellent alternative to traditional cement concrete. To expand the scope of application of geopolymer composites with plant fibers, further research is needed to evaluate their durability properties (frost resistance, water permeabil-

ity, and resistance to sulfate and chloride attacks). Limitations of the study include the lack of direct measurements of porosity, mercury porosimetry, or similar analysis.

4. Conclusions

Geopolymer composites with plant fibers have been developed. The study evaluated the density, CS, flexural strength, and water absorption of geopolymer composites dispersively reinforced with various types of plant fibers, including sisal (SF), flax (FF), and their combinations (SF + FF) at varying dosages (0%; 0.5%, 1.0%, 1.5%, and 2%). The microstructure of the geopolymer composite was also examined.

- (1) The CS of GCs reinforced with SF, FF, and SF + FF increased in the studied ranges from 0.5% to 2%. The optimal plant fiber content was 1%. The increase in CS for GCs with SF was 11.5% (45.5 MPa), with FF—8.6% (44.3 MPa), and with SF + FF—14.5% (46.7 MPa).
- (2) The flexural strength of GC reinforced with SF, FF, and SF + FF increased, with the optimal fiber content being 1%. The increase in flexural strength for GC with SF was 17.4% (5.4 MPa), with FF—13.0% (5.2 MPa), and with SF + FF—19.6% (5.5 MPa).
- (3) The lowest water absorption was recorded for GC reinforced with 1% SF, 1% FF, and 0.5% SF + 0.5% FF, amounting to 1.34%, 1.40%, and 1.25%, respectively.
- (4) The combination of sisal and flax fibers is the most effective, providing the maximum increase in strength properties and the lowest water absorption for GC. The results of dispersion analysis confirmed that the percentage of dispersed reinforcement has a greater effect on the properties of the composite than the type of fiber.
- (5) Geopolymer composites exhibit a uniform, rough structure with microcracks on the fracture surfaces. Clusters of zones of geopolymerization reaction products were recorded. The matrix-plant fiber interface of the plant fiber-reinforced GC is represented by a rounded region with elongated fibers, indicating the fiber's performance under mechanical stress.

The resulting geopolymer composites, reinforced with sisal and flax fibers, contribute to sustainable development by integrating renewable plant fibers and industrial by-products. The resulting GCs are suitable for the production of prefabricated structural elements, partitions and wall panels for low-rise construction, landscaping elements, temporary industrial structures with light loads, and for renovation work.

Author Contributions: Conceptualization, A.N.B., S.A.S., E.M.S., D.M.S., A.C. and N.S.; methodology S.A.S., A.N.B., E.M.S. and N.S.; software, A.P., A.C. and N.S.; validation, S.O., S.A.S., A.N.B., E.M.S. and D.M.S.; formal analysis, S.O., E.M.S. and A.N.B.; investigation, S.O., A.P., S.A.S., A.N.B., E.M.S., N.S., D.M.S. and A.C.; resources, D.M.S. and A.C.; data curation, S.O., A.P. and N.S.; writing—original draft preparation, S.A.S., A.N.B. and E.M.S.; writing—review and editing, S.A.S., A.N.B. and E.M.S.; visualization, D.M.S. and A.N.B.; supervision, A.N.B.; project administration, S.A.S.; funding acquisition, S.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by the grant of the Russian Science Foundation No. 25-29-00535, <https://rscf.ru/en/project/25-29-00535/> (accessed on 27 July 2026).

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to acknowledge the administrations of Don State Technical University and Necmettin Erbakan University for their resources and support.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SF	Sisal fiber
FF	Flax fiber
GC	Geopolymer composites
C-S-H	Calcium silicate hydrate
GGBFS	Ground granulated blast furnace slag
CS	Compressive strength
FS	Flexural strength

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