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Mechanical properties and microstructure of plant fiber reinforced BFS-MS geopolymer: an orthogonal design approach

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Foundation pit engineering usually encounters the problems of foundation reinforcement and mud soil (MS) disposal. This study proposes a solidification technology utilizing blast furnace slag (BFS)-MS based geopolymer, enhanced by renewable plant fibers, to achieve resource utilization of MS. The key parameters including activator modulus, alkali content, water-to-solid ratio, and MS replacement rate were systematically optimized through orthogonal experimental design. Based on considering the mechanical properties and economy, the pretreated wood (WF), jute (JF) and bamboo (BF) fibers were incorporated respectively to study the influence of plant fiber type and content on the mechanical properties of geopolymer. The results demonstrated that the optimal parameters for BFS-MS precursors were activator modulus 1.7 and alkali content 0.2. The BFS-MS geopolymer under the optimal ratio of 28 days can reach 43.56 MPa, maintaining excellent potential for engineering application even at 30% MS replacement. At 1.0% dosage, WF, JF and BF enhanced the 28-day compressive strength by 27.80%, 12.35% and 29.05% respectively. The microstructural analysis revealed that geopolymer gels derived from BFS hydration dominated early strength development, while potentially active minerals in MS contributed to later stage strength enhancement. This study provides theoretical and technical foundations for MS utilization and fiber-reinforced geopolymer design in sustainable construction practices.

KEYWORDS

mud soil, blast furnace slag, plant fibers, orthogonal experimental design, uniaxial compressive strength, geopolymer

1 Introduction

The disposal and resource utilization of MS remain persistent challenges in deep foundation pit engineering, dredging projects, and related fields. The conventional approaches are mainly landfill or dewatering and drying, which have bottlenecks such as land resource occupation, secondary pollution risk and high carbon emission (Jia et al., 2024; Zhao et al., 2024; Wang and Hao, 2024). In current stabilization practices, MS is predominantly used as an inert filler blended with cement or

lime, functioning as a physical additive rather than a chemically active component (Cao et al., 2024). This results in suboptimal material utilization and compromised long-term stability of solidified matrices (Wang Q. et al., 2024). Although emerging techniques like chemical modification and bio-cementation have partially improved the mechanical properties of MS-based materials, they still face issues such as low stabilization efficiency, high costs, and poor environmental compatibility (Wei et al., 2023; Cui et al., 2022; James, 2020). Notably, MS contains abundant silicates and aluminates, demonstrating potential as a geopolymer precursor. By activating its inherent reactivity, MS can transform into the primary cementitious phase rather than merely serving as a passive reinforcement. This enables its conversion from waste material to active cementitious component (Zhang et al., 2024; Nematollahi et al., 2017; Davidovits, 1991).

Geopolymer technology has long attracted attention for its low-carbon characteristics and resource recovery potential for silica-alumina-rich wastes. Its fundamental mechanism involves alkaline activation of Si and Al-rich precursors to develop substantial strength (Davidovits, 1989; Wang et al., 2005). Under optimal alkaline conditions, Si and Al minerals in MS undergo depolymerization to form siloxane and aluminate units, which subsequently polymerize into cementitious materials with good mechanical properties (Van-Jaarsveld et al., 1997; Gluk and hovsky, 1965; Almutairi et al., 2021). Zhang et al. (Zhang et al., 2023a) achieved a maximum UCS of 1.88 MPa for MS-based geopolymers using straw ash and sodium silicate as composite activators. Similarly, Kong et al. (Kong et al., 2023) reported a 28 days strength of 4.29 MPa through co-stabilization of MS with MgO and industrial slag. Conventional alkaline activation methods are difficult to significantly enhance MS's mechanical performance due to its "calcium-deficient" nature and high content of inert components formed by precipitation (Mikhailova et al., 2019). Lu et al. (2022) demonstrated synergistic alkali-thermal activation of MS, achieving 7 days and 28 days strengths of 8.93 MPa and 16.37 MPa, respectively. While effective, this method incurs substantial costs, highlighting the need to introduce calcium-rich precursors like blast furnace slag to supplement early -stage strength development in MS based geopolymers (Zhang et al., 2022). Lv et al. (2022) developed loess-slag geopolymer composites (LSGC) using loess and slag as precursors. Their results showed that at the optimal 1:1 ratio, the LSGC exhibited satisfactory workability and setting time, achieving a 28-day UCS of approximately 14.61 MPa with a dense and stable microstructure.

In the study of multifactor effects on geopolymer properties, orthogonal experimental design (OED) can identify key influencing factors and their optimal combinations effectively through partial implementation strategies, significantly improving experimental efficiency (Wang Y. et al., 2024; Cai et al., 2023). Chen et al. (2025) conducted a three-factor, four-level L_{16} (4^3) OED study and found that a drainage sludge replacement rate of 30%, sodium silicate modulus of 1, and liquid-solid ratio of 0.3 yielded the highest 28-day compressive strength (6.78 MPa) for geopolymer containing drainage sludge, fly ash, and coal gangue. Similarly, Li et al. (2024a) conducted a three-factor L_9 (3^3) orthogonal experiment examining alkali equivalent, Si/Al ratio, and hot-pressed curing time. Their results demonstrated that alkali equivalent

had the greatest impact on the compressive strength of hot-pressed metakaolin-fly ash based geopolymers. Within the 4–8 wt% alkali equivalent range, the maximum difference in 28-day compressive strength reached 190.72 MPa. Concurrently, fiber-modified construction materials have seen considerable advancement. Zhong et al. (2024) enhanced the 28 days compressive strength of lithium slag-based geopolymer by 14.9% through 0.1% incorporation of carboxylated multi-walled carbon nanotubes. Chen et al. (2018) reported 39.4% and 32.3% improvements in flexural strength for metakaolin-based geopolymers using 5 wt% polyacrylic emulsion or 0.2 v/v% polypropylene fiber, respectively. As renewable reinforcements, plant fibers have gained traction in green construction materials due to their low density, high specific strength, and carbon neutrality. Their cellulose microfibril structures effectively enhance composite toughness and suppress crack propagation (Withana et al., 2024; Di Sarno et al., 2024; Zainal et al., 2024). However, research on plant fibers in geopolymer systems remains nascent, necessitating systematic studies to elucidate their impact on mechanical performance and underlying mechanisms (Kuqo et al., 2023a; Yang et al., 2023).

This study proposes an in-situ MS stabilization technology based on a BFS-MS geopolymer system. The key parameters such as activator modulus, alkali content, water-to-solid ratio and MS replacement rate were optimized by orthogonal experiments. On the basis of considering the mechanical properties and economy, different types of plant fibers were added to the slag-mud soil based geopolymer to study the influence of plant fiber type and content on its mechanical properties, and to study the internal mechanism of its mechanical properties evolution. The findings aim to advance the resource utilization of MS and plant fibers in sustainable construction materials.

2 Experimental

2.1 Materials

2.1.1 Mud soil (MS)

The mud soil used in this study was taken from the bottom soil of a deep foundation pit project in Hangzhou, Zhejiang Province, China, as shown in Figure 1. The organic matter pollution of the MS was light, and there was no obvious odor after air drying. A series of tests determined the basic properties of MS: specific gravity of approximately 2.68, initial moisture content ranging from 25% to 65%, plastic limit of 25.3%, and liquid limit of 45.6%. The MS of the foundation pit engineering project is naturally dried and condensed, and the block is large. Firstly, it is preliminarily crushed, then it is ground by vibrating mill, and finally screened by 200 mesh (0.074 mm) sieve. The MS treated by the above process can be used for raw material property test and sample preparation.

The XRF test results of MS are shown in Table 1, indicating the weight percentage of each element. It is showed that both BFS and MS contain many potential active components, such as SiO_2 and Al_2O_3 . The LOI refers to the loss of ignition, which means that the MS that loses free water after drying continues to burn for a long enough time under certain high temperature conditions, and the mass lost in this process accounts for the percentage of the original

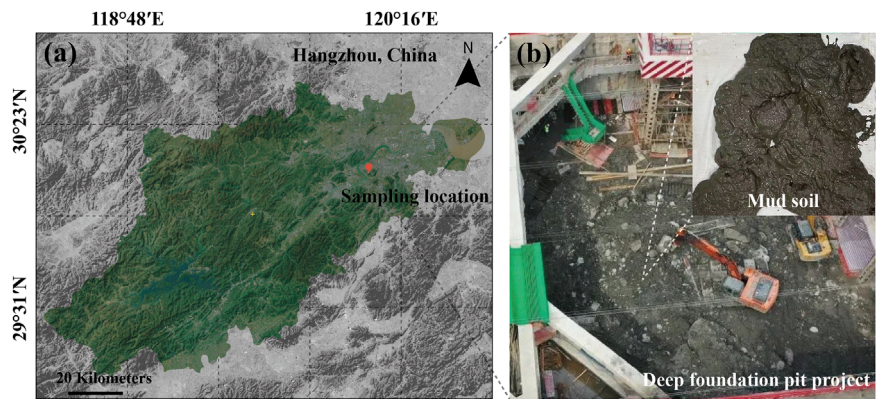


FIGURE 1 Sampling location and morphology of mud soil. (a) Engineering location; (b) Sampling and morphology of mud soil.

TABLE 1 The chemical composition of mud soil (wt%).

Chemical composition	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	Other	LOI
Weight content (%)	46.27	25.15	4.76	6.28	2.94	5.62	8.98

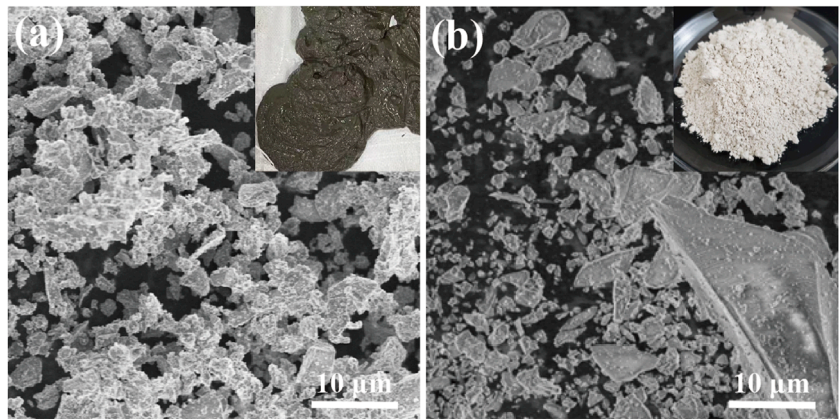


FIGURE 2 The appearance and micro-morphology of raw materials (a) MS; (b) BFS.

sample mass. The micro-morphology of MS is shown in Figure 2A, which is rod-like or granular.

2.1.2 Blast furnace slag (BFS)

Blast furnace slag (BFS) is a molten material with silicate and aluminosilicate as the main components after quenching and granulation when smelting pig iron in the blast furnace. The BFS was provided by a mineral product processing plant in Hebei Province, China. It is an S105 grade mineral powder. This gray powder has a specific surface area of 480 m²/kg, a density of 3.1 g/cm³, and a loss on ignition of 0.84%. The chemical composition (in the form of oxides of each element) of the BFS was analyzed using an X-ray fluorescence (XRF) analyzer (ZETIUM, PANalytica B.V., Netherlands), and the results are shown in Table 2. Figure 2B is

the apparent and micro-morphology of BFS, which can be seen as irregular flake or granular, and most of the particle size range is below 10 µm.

2.1.3 Sodium silicate-sodium hydroxide type activator (SS)

The activator used in this study was a mixture of sodium silicate and sodium hydroxide. Sodium silicate and sodium hydroxide are provided by Myrel Chemical Technology Co., Ltd, Shanghai, China. Sodium silicate is a white powder solid with a modulus of two and a purity of 99.7%. Sodium hydroxide is a white granular solid with a purity of 99.7%.

Modulus is one of the important parameters of the SS, which refers to the value of *n* in the general formula of sodium silicate

TABLE 2 The chemical composition of blast furnace slag (wt%).

Chemical composition	CaO	SiO ₂	Al ₂ O ₃	SO ₃	Fe ₂ O ₃	MgO	Other
Weight content (%)	34.00	34.50	17.70	1.64	1.03	6.01	5.12

FIGURE 3
The appearance of plant fibers (a) WF; (b) JF; (c) BF.

$\text{Na}_2\text{O} \cdot n\text{SiO}_2$. The smaller the value of n , the stronger the alkalinity of the SS, and the higher the solubility in water. In order to configure the SS with specified modulus, the mass of sodium hydroxide added to sodium silicate with a modulus of two can be calculated according to Formula 1:

$$m_{(\text{NaOH})} = 2 \cdot \text{Ar}_{(\text{NaOH})} \cdot \left(\frac{x-c}{c} \right) \frac{m_{(\text{Na}_2\text{O} \cdot x\text{SiO}_2)}}{\text{Ar}_{(\text{Na}_2\text{O} \cdot x\text{SiO}_2)}} \quad (1)$$

Where, $m_{(\text{NaOH})}$ is the amount of sodium hydroxide, g; c is the modulus of the SS; x is the modulus of the sodium silicate; $\text{Ar}_{(A)}$ is the relative molecular mass of substance A.

2.1.4 Plant fibers (PF)

Wood fiber (WF), as shown in Figure 3a, 40–80 mesh, 1–3 mm in length, 2.1–2.3% in elongation at break, self-processed, produced from a wood market in Hangzhou, China.

Jute fiber (JF), as shown in Figure 3b, 30–50 mesh, length of 1–3 mm, elongation at break of 2.7–3.1%, self-processed, produced from a hemp product Co., Ltd. in Wuhan, China.

Bamboo fiber (BF), as shown in Figure 3c, 30–50 mesh, length of 1–3 mm, elongation at break of 3.5–3.8%, self-processed, produced from a wood market in Hangzhou, China.

Each plant fiber was dried to absolute dryness and sealed at $103^\circ\text{C} \pm 2^\circ\text{C}$.

2.2 Experimental design and sample preparation

The mechanical properties of slag-mud soil (BFS-MS) geopolymers are critically influenced by four compositional parameters: the modulus of SS, the SS alkali content (expressed as $m(\text{Na}_2\text{O})/m(\text{H}_2\text{O})$ ratio), the water-solid ratio (the mass ratio of water to total solid precursors), and mud soil replacement rate (expressed as $m(\text{MS})/m(\text{BFS} + \text{MS})$ ratio). Specifically, the first two factors are

related to the composition and dosage of SS. They directly determine the alkalinity of the reaction system and the amount of reactive silica introduced. Since SS is a high-energy-consumption and high-cost raw material, its parameter selection significantly affects the economic feasibility of BFS-MS based geopolymers. The water-solid ratio is closely linked to the workability during preparation and the final material performance. Different application scenarios may require different values for this parameter. The mud soil replacement rate is the key focus of this study. It directly influences both the utilization efficiency of MS waste and the balance of material properties. In this study, these variables were systematically optimized using an orthogonal experimental design (OED) to establish performance-composition relationships. On the basis of considering the mechanical properties and economy, different types of plant fibers (wood, jute, bamboo) were added to the slag-mud soil based geopolymer to study the influence of plant fiber type and content on its mechanical properties, and to study the underlying mechanism of its mechanical properties evolution.

2.2.1 Composition design and preparation of slag-mud soil based geopolymers

The characteristic of the OED method is to use the orthogonal table to scientifically arrange the experiment, select the representative points with the characteristics of “uniform dispersion, neat and comparable” for the experiment (Yuan et al., 2022). Its advantage is that it can systematically consider multiple factors and their interactions to ensure the comprehensiveness and reliability of the test results. At the same time, it has economic efficiency by greatly reducing the number of tests, improving test efficiency, and reducing time and cost (Luo et al., 2022).

In this study, the modulus of the SS, the alkali content of SS, the water-solid ratio, the mud soil replacement rate were selected as four factors of orthogonal design. The range and step length of each factor are selected on the basis of reference to relevant literature (Lu et al., 2022; Lin et al., 2025; Kina et al., 2025). Specifically, the

TABLE 3 Orthogonal experimental design table of the slag-mud soil based geopolymer.

Sample number	Factors				Materials mass (g)					UCS (MPa)		
	A	B	C	D	BFS	MS	Sodium silicate	Sodium hydroxide	Water	3 days	7 days	28 days
SM 1	1.3	0.15	0.3	0.00	1,000	0	85.86	20.32	300	28.53	30.13	32.20
SM 2	1.3	0.20	0.4	0.45	550	450	152.65	36.13	400	19.33	24.47	31.34
SM 3	1.3	0.25	0.5	0.15	850	150	238.51	56.45	500	24.14	25.21	37.42
SM 4	1.3	0.30	0.6	0.30	700	300	343.45	81.29	600	24.60	28.94	39.59
SM 5	1.5	0.15	0.4	0.30	700	300	132.10	19.35	400	24.67	27.96	33.87
SM 6	1.5	0.20	0.3	0.15	850	150	132.10	19.35	300	32.84	36.54	40.21
SM 7	1.5	0.25	0.6	0.45	550	450	330.24	48.39	600	28.63	32.02	39.78
SM 8	1.5	0.30	0.5	0.00	1,000	0	330.24	48.39	500	31.46	35.09	38.45
SM 9	1.7	0.15	0.5	0.45	550	450	187.14	14.52	500	24.24	31.51	42.02
SM 10	1.7	0.20	0.6	0.00	1,000	0	299.42	23.23	600	31.40	31.88	39.43
SM 11	1.7	0.25	0.3	0.30	700	300	187.14	14.52	300	26.38	28.71	32.77
SM 12	1.7	0.30	0.4	0.15	850	150	299.42	23.23	400	33.03	33.70	38.57
SM 13	1.9	0.15	0.6	0.15	850	150	250.98	5.81	600	28.75	31.00	32.72
SM 14	1.9	0.20	0.5	0.30	700	300	278.87	6.45	500	29.92	33.37	41.26
SM 15	1.9	0.25	0.4	0.00	1,000	0	278.87	6.45	400	31.83	35.17	38.21
SM 16	1.9	0.30	0.3	0.45	550	450	250.98	5.81	300	17.64	24.80	33.44

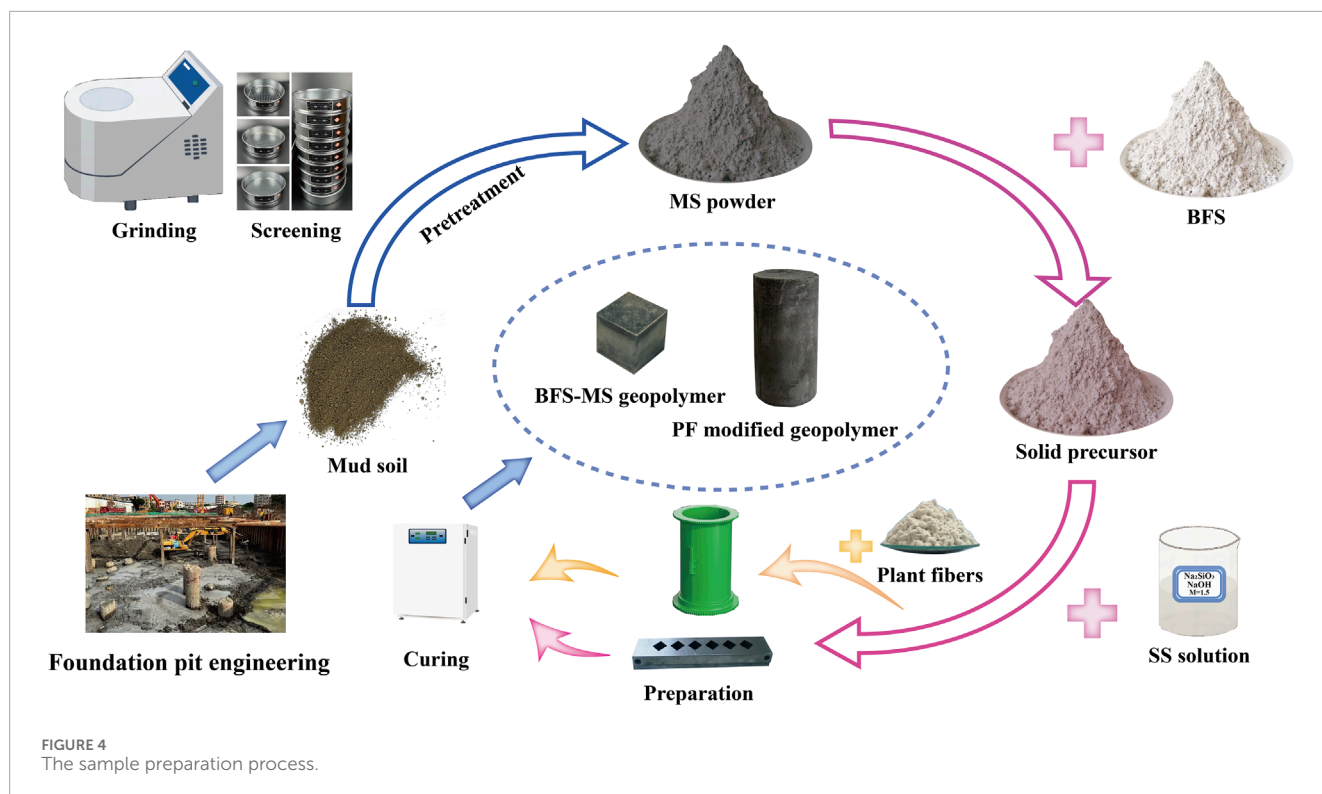
modulus of the SS (factor A) ranges from 1.3 to 1.9, and the step length is increased by 0.2. The alkali content of SS (factor B) ranges from 0.15 to 0.30, and the step length is increased by 0.05. The water-solid ratio (factor C) ranges from 0.3 to 0.6, and the step length is increased by 0.1. Additionally, the range of the mud soil replacement rate in this study was determined based on the activity index of the solid waste raw materials. According to the Ground granulated blast furnace slag used for cement, mortar, and concrete standard (GB18046-2017) (National Cement Standardization Technical Committee 2017), the 7-day activity index of BFS was measured as 88%, while that of MS was 45%. This indicates that the activity of MS is significantly lower than that of BFS. In the precursor composed of MS and BFS, an excessive proportion of MS would lead to insufficient material performance. Therefore, the mud soil replacement rate was selected within the range of 0–0.45, with an increment step of 0.15. The experimental design of four factors and four levels is shown in Table 3. The quantities of all other materials were calculated and recorded in the table, using 1,000 g of solid waste precursor as the baseline reference.

The preparation process of the slag-mud soil based geopolymer is illustrated in Figure 4, consisting of three key steps. First, precisely weighed MS powder was uniformly blended with BFS to form the

solid precursor (SP). The SS solution was then prepared by mixing sodium silicate-sodium hydroxide type activator with the required amount of water. Finally, the SP was combined with the SS solution and thoroughly mixed to form a relatively homogeneous slurry. This slurry was cast into 20 × 20 × 20 mm molds, vibrated for compaction, and cured at 20°C ± 2°C with 65%–70% relative humidity. As described in Section 2.1, all precursor materials particle sizes including MS and BFS were below 75 μm. It ensured sample homogeneity, minimizing potential size effects on mechanical property measurements - a well-established approach frequently reported in literature (Brustolin et al., 2024; Li et al., 2024b). After 24 h of room temperature curing, the demolded samples were aged to target test periods for subsequent macro- and micro-scale characterization.

2.2.2 Preparation of plant fiber modified geopolymers

On the basis of comprehensive consideration of the mechanical properties and economy of slag-mud soil based geopolymer, different types of plant fibers were added to study the influence of fiber type and content on its mechanical properties. The fiber modification protocol comprised two stages: 1) Fiber pretreatment: Raw fibers were immersed in 5 wt% NaOH solution at 60°C for 2 h



to remove hemicellulose, followed by rinsing to neutrality, oven-drying at 80°C for 24 h, and mechanical cutting into 1–3 mm segments, which were then stored in sealed containers; 2) Composite fabrication: Pretreated fibers were homogeneously blended with the SP (BFS-MS mixture), followed by alkali activation and molding as detailed in Section 2.2.1. Furthermore, existing studies indicate that excessive fiber content can lead to fiber clustering, void formation, and poor dispersion within the matrix (Yang et al., 2021). This results in reduced workability of the slurry, as well as decreased compressive strength and impact resistance. In contrast, a low fiber dosage (below 2%) demonstrates better reinforcement and toughening effects (Li et al., 2023; Yang et al., 2025; Hua et al., 2025). Therefore, this study prepared plant fibers modified geopolymer samples with fiber contents of 0.5 wt%, 1.0 wt%, and 1.5 wt%. It should be noted that unlike the 20 mm cubic samples used for MS-BFS geopolymers in Section 2.2.1, the plant fiber modified BFS-MS geopolymers required larger dimensions due to the 1–3 mm fiber length. To ensure sample homogeneity, cylindrical samples measuring 50 mm in diameter and 100 mm in height were adopted for all PF-modified geopolymer samples. Triplicate samples for each formulation were cured under standardized conditions to ensure reproducibility. The preparation workflow is schematically illustrated in Figure 4.

2.3 Testing method

2.3.1 Uniaxial compressive strength (UCS)

The uniaxial compression tests were conducted on solidified samples at 3, 7, and 28 curing days using a DW1210 universal testing machine (50 kN capacity)

under strain-controlled loading (0.5 mm/min), following Common Portland Cement (GB 175–2023) standards (National Cement Standardization Technical Committee, 2023). The UCS was defined as the peak stress at sample failure (Haifeng et al., 2022).

2.3.2 X-ray diffraction (XRD)

The phase composition analysis was performed using a PANalytical Xpert-Pro diffractometer (Cu-K α radiation, $\lambda = 1.5406 \text{ \AA}$) with 2θ ranging 20° – 60° at $5^\circ/\text{min}$ (step size 0.02°). Powdered samples ($<75 \mu\text{m}$, 200-mesh) were prepared to ensure diffraction signal accuracy.

2.3.3 Scanning electron microscopy (SEM)

The microstructural characterization was carried out on a JEOL JSM-6501 SEM at 5 kV. The samples were gold-coated to enhance conductivity. Secondary electron imaging revealed surface morphology and fiber-matrix interactions (Zhang et al., 2023b).

3 Results and discussions

3.1 The UCS of the slag-mud soil based geopolymer

The uniaxial compressive strength results of slag-mud soil geopolymer samples are summarized in Table 3, with the temporal evolution of average UCS across groups illustrated in Figure 5.

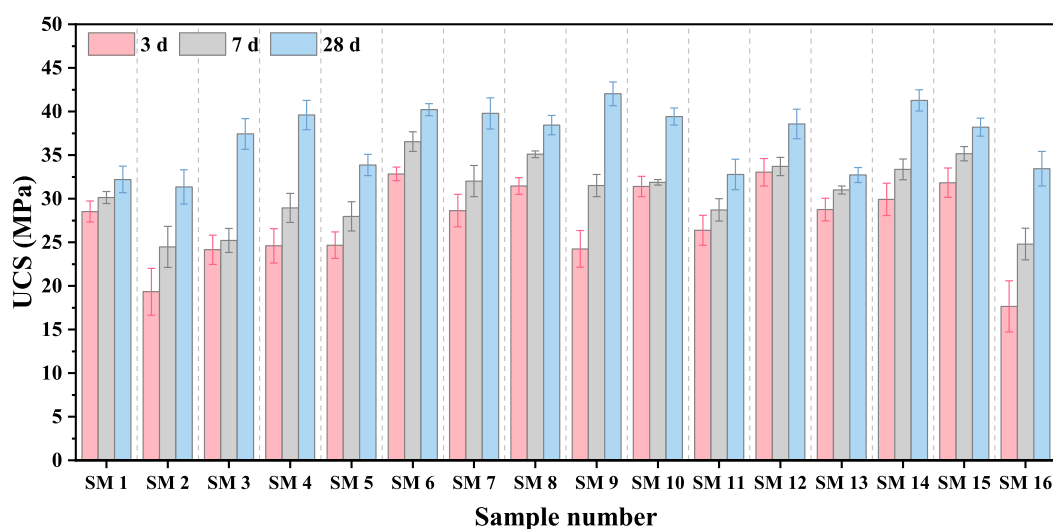


FIGURE 5
The average compressive strength of each group of samples.

The BFS-MS based geopolymer samples exhibited considerable early-age strength development. All sample groups achieved 3-day UCS values above 20 MPa, representing over 50% of their respective 28-day strengths. Notably, certain groups (SM1, SM6, SM8) demonstrated particularly rapid strength gain, attaining more than 80% of their 28-day UCS within 3 days, highlighting the material's early-strength characteristics. These groups with faster early strength development consistently featured lower levels of Factor D, primarily attributable to the abundant reactive calcium sources in the BFS precursor that significantly accelerated geopolymerization. At 28 days, SM9 showed the highest UCS (42.02 MPa), while SM2 displayed the lowest (31.34 MPa). However, these samples did not consistently maintain maximum or minimum strength values across all curing ages, indicating that the influence of factor levels on UCS varies with curing time. This age-dependent behavior necessitates further examination through orthogonal analysis (Wang Y. et al., 2024; Alameri et al., 2025).

3.2 Range analysis

Range analysis was performed on the unconfined compressive strength results of slag-mud soil based geopolymers using orthogonal design methodology. The calculation procedure involved two key parameters: k_i and R . The complete statistical results are presented in Table 4. In which, K_i represents the summation of UCS values when the factor is set at level i , where the average value k_i reflects the systematic variation induced by adjusting the factor level. The range parameter R , defined as the difference between maximum and minimum k_i values, quantitatively indicates the sensitivity of UCS to each individual factor.

Through this analytical approach, the relative importance of different factors affecting geopolymer strength could be systematically evaluated. Larger R values correspond to greater

influence on the mechanical properties, allowing clear identification of dominant and secondary controlling factors (Zhang et al., 2024). Taking the UCS of 3 days as an example, the R-value analysis revealed the following significance ranking of influencing factors: D (mud soil replacement rate) > A (SS modulus) > C (water-solid ratio) > B(SS alkali content). This demonstrates that factor D exerted the most important influence on the early strength development of slag-mud soil based geopolymers, while factor B showed the least impact. Furthermore, the results in Table 4 reveal non-monotonic relationships between factors and performance metrics. Taking the SS modulus (Factor A) as an example: within the tested range, the UCS of 3 days initially increased with rising SS modulus up to 1.5, beyond which further modulus increases resulted in gradual strength reduction. To better illustrate the influence of each factor level on the target value, Figures 6a–d graphically shows the variation trends of average UCS with respect to different level settings for each experimental factor. The theoretically optimal combination was obtained by selecting the peak performance level for each factor. For the UCS of 3 days, this corresponded to the A2(SS modulus)-B2(SS alkali content)-C4(water-solid ratio)-D1 (mud soil replacement rate) parameter set. The significance ranking of each factor's influence on the experimental objectives and their optimal combinations were determined through k_i and R analysis, with all results presented in Table 4.

For Factor A (SS modulus), the UCS of samples at different curing ages exhibited a consistent trend of initial increase followed by decrease as the modulus increased. The optimal SS modulus was 1.5 for maximum 3-day and 7-day strength, while 1.7 produced the highest 28-day strength. When the SS modulus was below the optimal value, the alkali activator provided insufficient reactive silicate oxide monomers, potentially leading to incomplete polycondensation reactions (Cui et al., 2017). This resulted in reduced mechanical properties of the samples. As shown in

TABLE 4 Range analysis table.

Factors	UCS of 3 days (MPa)				UCS of 7 days (MPa)				UCS of 28 days (MPa)			
	A	B	C	D	A	B	C	D	A	B	C	D
K_1	96.60	106.19	105.39	123.22	108.76	120.60	120.18	132.27	140.55	140.81	138.62	148.28
K_2	117.60	113.49	108.86	118.77	131.62	126.26	121.29	126.44	152.31	152.24	141.98	148.92
K_3	115.05	110.98	109.77	105.56	125.79	121.11	125.19	118.99	152.79	148.18	159.15	147.49
K_4	108.15	106.74	113.38	89.85	124.32	122.53	123.83	112.79	145.63	150.04	151.52	146.58
k_1	24.15	26.55	26.35	30.81	27.19	30.15	30.04	33.07	35.14	35.20	34.65	37.07
k_2	29.40	28.37	27.21	29.69	32.90	31.56	30.32	31.61	38.08	38.06	35.50	37.23
k_3	28.76	27.75	27.44	26.39	31.45	30.28	31.30	29.75	38.20	37.05	39.79	36.87
k_4	27.04	26.68	28.34	22.46	31.08	30.63	30.96	28.20	36.41	37.51	37.88	36.65
R	5.25	1.82	2.00	8.34	5.72	1.42	1.25	4.87	3.06	2.86	5.13	0.58
Significance	D>A>C>B				A > D > B > C				C>A>B > D			
Preferred scheme	A2-B2-C4-D1				A2-B2-C3-D1				A3-B2-C3-D2			

Figure 6b, the lower SS modulus significantly decreased sample strength, and this weakening effect persisted throughout the curing period. Conversely, when the SS modulus increased beyond the optimal value, the alkalinity of the solution system decreased significantly. This reduction in alkalinity slowed both the precursor dissolution and geopolymerization reaction rates (Zhao et al., 2022). As illustrated in Figure 6a, elevated SS modulus values exhibited a more pronounced effect on the early-age UCS of the samples. However, the negative impact of excessively high SS modulus gradually diminished with prolonged curing duration.

For Factor B (SS alkali content), the optimal value for maximum strength at all curing ages was consistently 0.20 within the studied range. When the alkali content fell below this value, both alkalinity and silicate oxide monomer concentration in the reaction system decreased significantly, leading to reduced UCS across all curing ages (Zhang et al., 2022). However, increasing the alkali content beyond 0.20 resulted in strength reduction. This may be attributed to excessive alkali causing detrimental effects such as efflorescence, which was observed during testing.

For Factor C (water-solid ratio), the optimal values varied with curing age within the studied range. The 3-day strength peaked at a water-solid ratio of 0.6, while the highest 7-day and 28-day strengths occurred at 0.5. During early reactions, higher water-solid ratios reduced solution viscosity, facilitating ion exchange and enhancing strength development (Davidovits, 1991). However, in later curing stages, excess water caused detrimental effects including significant drying shrinkage stress, ultimately reducing the final strength (Mikhailova et al., 2019).

For Factor D (mud soil replacement rate), the range analysis showed that sample strength approximately decreased as the MS replacement rate increased across all curing ages. Within the studied range, the optimal replacement rate was 0 for maximum 3-day and 7-day strength, while 0.15 yielded the highest 28-day strength. Figure 6d revealed that the MS replacement rate significantly affected early-age strength. A 0.45 replacement rate reduced 3-day strength to 72.9% of the reference value, though this recovered to 98.9% by 28 days. This improvement suggests that mud soil actively participated in geopolymerization during later curing stages, contributing to strength development. Moreover, when the MS replacement rate was 0.3, the sample achieved 85.7%, 90.0%, and 99.5% of the original strength at 3, 7, and 28 days respectively. This formulation maintains satisfactory mechanical performance across all curing ages while significantly reducing material costs, demonstrating excellent potential for engineering applications.

The UCS variation is presented in Figure 7. Based on the R-value analysis, the significance ranking of each factor's influence on the target property was determined as shown in Table 4. The range analysis revealed that the optimal composition for achieving maximum 28-day UCS consists of: SS modulus of 1.7, SS alkali content of 0.2, water-solid ratio of 0.5, and MS replacement rate of 0.15. A verification test confirmed this optimized formulation yielded a UCS of 43.56 MPa, demonstrating good agreement with the predicted results. This optimal combination balances multiple competing factors: sufficient alkalinity for activation, appropriate viscosity for workability, and adequate reactive components for geopolymer formation. The experimental validation confirms the reliability of the orthogonal design approach for slag-MS based geopolymer optimization.

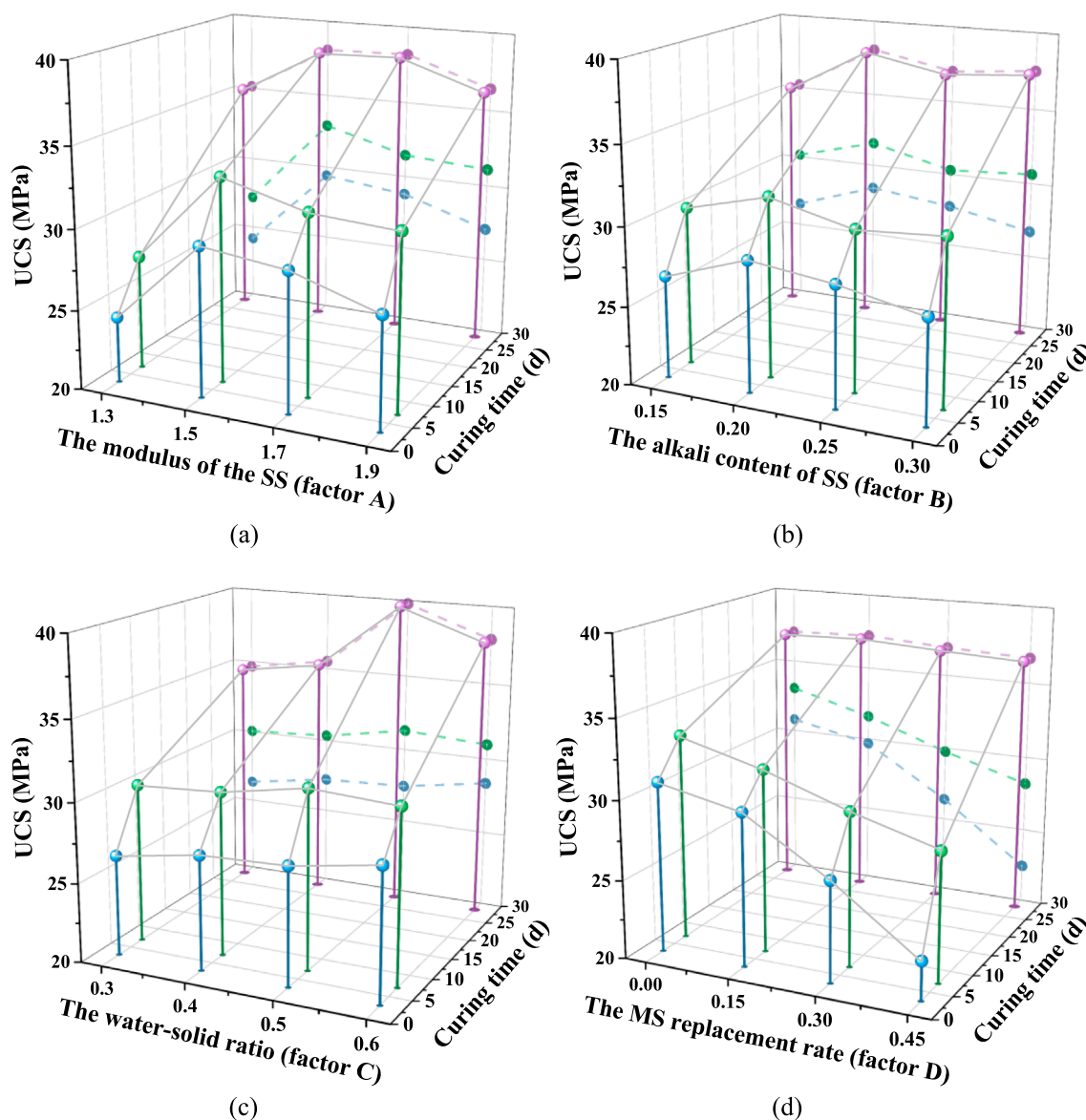


FIGURE 6

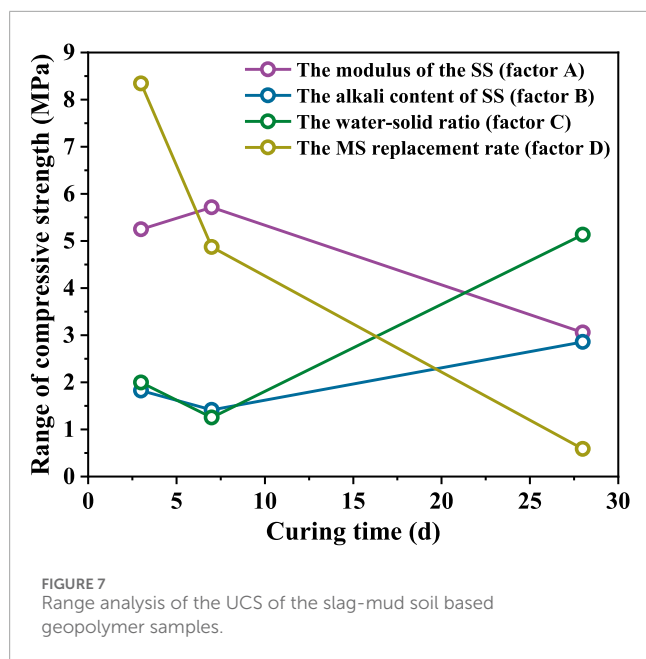
The effect trend of each factor on the UCS of the slag-mud soil based geopolymer samples. (a) Effect trend of factor A on UCS; (b) Effect trend of factor B on UCS; (c) Effect trend of factor C on UCS; (d) Effect trend of factor D on UCS.

3.3 Variance analysis

In orthogonal experimental design, the observed variations in UCS may result from either controlled factor-level changes or uncontrolled experimental errors. While range analysis effectively identifies influential factors, it cannot statistically separate these effects from random experimental variations. Analysis of variance provides a more rigorous approach, enabling quantitative evaluation of each factor's significance through F-tests. This method distinguishes systematic factor effects from random noise, offering greater reliability for optimization decisions (Nguy $\tilde{e}$ et al., 2023). The variance analysis results contain key parameters of

the orthogonal experimental system: the sum of squares S_k , mean square value V_k , degrees of freedom f , and F-value F_k . A higher F_k value indicates greater significance of the corresponding factor. The complete variance analysis results are provided in Table 5.

It is found that the mud soil replacement rate has the most significant effect on the UCS of slag-mud soil based geopolymer samples, especially during the early stage of curing (≤ 7 days). Moreover, the effects of the mud soil replacement rate and the modulus of the SS on the UCS of the samples decreased with the age of curing. The effect of the water-solid ratio increases with the age of curing.



3.4 Effect of plant fiber on UCS of geopolymer

According to the results of orthogonal test, the slag-mud soil based geopolymer was selected for plant fiber modification under the following parameters: the modulus of the SS is 1.7, the alkali content of SS is 0.2, the water-solid ratio is 0.5 and the MS replacement rate is 0.30. The purpose of this choice is to use SS as little as possible to obtain the most significant economic benefits, while maintaining a high UCS to consume and utilize MS as much as possible. As a control group, the slag-mud soil based geopolymer without any plant fiber was prepared under this parameter. The UCS results are shown in Table 6. The UCS of fiber-modified geopolymer samples and their increments as shown in Figure 8.

The optimal reinforcement effect was observed for WF and BF at fiber contents of 1.0%–1.5%, with particularly significant early strength enhancement. The maximum UCS increase reached 48.23% at 3 days for WF modified geopolymers and 48.36% for BF modified counterparts. This enhancement mechanism can be attributed to two primary factors: 1) The smooth surface morphology of WF and BF facilitated uniform dispersion within the matrix, enabling effective crack bridging and load transfer; 2) Alkali treatment exposed cellulose hydroxyl groups, which formed strong hydrogen bonds with the geopolymer's Si-Al network, promoting pore filling and significantly improving early strength (Fioroni et al., 2025). In contrast, the rough surface of JF fibers tended to induce agglomeration, creating stress concentration points under loading (Kuqo et al., 2023b). JF modified samples exhibited a distinct threshold effect: at 0.5% content, 28 days UCS decreased by 7.88%, while at 1.0% content, UCS increased by 12.35%, followed by a sharp decline to 4.73% at 1.5% content. Furthermore, existing studies confirm that JF provides limited enhancement or even negatively affects performance (Yang et al., 2021). Korniejenko et al. (Korniejenko et al., 2018) observed

that 1% coconut fiber content yielded a 26.55% improvement in 28-day compressive strength for geopolymers, which is slightly lower than the enhancements achieved by both WF and BF in our study, with cotton fibers showing even more modest gains.

In addition, the reinforcement efficiency of all fiber types diminished with prolonged curing, with 28 days UCS increases generally falling below 30%. This phenomenon stems from two mechanisms. On the one hand, with the increase of age, the strength of geopolymer matrix tends to be stable. At this time, the relative enhancement efficiency of plant fiber decreases. On the other hand, Prolonged exposure to the alkaline environment induces cellulose depolymerization in plant fibers, accompanied by interfacial debonding and cracking, leading to reduced late-age strength enhancement (Glaus and Van Loon, 2008). Therefore, when selecting plant fibers for geopolymer modification, easily dispersible fibers such as WF and BF are recommended. An optimal fiber content of approximately 1.0% can provide effective reinforcement, particularly during the early stages of strength development.

3.5 XRD analysis

To investigate the strength origins of slag-mud soil-based geopolymer, XRD analysis was conducted on raw materials and SM 9 with the highest strength at 28 days in the orthogonal tests. Their XRD patterns are shown in Figure 9.

In MS, quartz and illite dominate as primary mineral components. The sharp and narrow peaks in the XRD pattern indicate well crystallized mineral phases, which is the result of long-term geological stabilization. Although exhibiting low reactivity, these minerals provide essential Si and Al components to the reaction system, contributing to the late-stage strength development of samples. For BFS, quartz, calcite, and mullite constitute the main mineral phases. The broad and low-intensity diffraction peaks in pattern suggest lower crystallinity and higher pozzolanic activity, which account for the early strength enhancement of samples. In SM 9, the XRD pattern demonstrates attenuated characteristic peaks of raw materials and the emergence of new phases. At about 29.06°, an amorphous dispersion peak appears, which is generally considered to be a mixed phase of geopolymer products C-S-H and C-(N)-A-S-H, and also a cementitious phase product that maintains the strength of the samples (Wang et al., 2023; Pan et al., 2018). The diffraction peaks of calcium carbonate were also observed in the samples, which may originate from the calcite in the raw materials and secondary hydration products. In addition, the Al_2O_3 peaks in SM-9 may originate from the decomposition products of clay minerals in MS (Zhang et al., 2024). These products also act as weak impurities filling the geopolymer samples, negatively affecting the sample's integrity and load-bearing capacity.

3.6 SEM analysis

Figure 10 displays the micro-morphology of plant fiber-modified geopolymer with a 1.5% fiber dosage. While direct

TABLE 5 Analysis of variance results for the UCS of the slag-mud soil based geopolymer samples.

Source of variance	<i>f</i>	UCS of 3 days			UCS of 7 days			UCS of 28 days		
		<i>S</i>	<i>V</i>	<i>F</i>	<i>S</i>	<i>V</i>	<i>F</i>	<i>S</i>	<i>V</i>	<i>F</i>
A	3	66.12	22.04	0.95	71.53	23.84	0.93	25.61	8.54	0.31
B	3	9.15	3.05	0.13	4.91	1.64	0.06	18.42	6.14	0.22
C	3	8.08	2.69	0.12	3.95	1.32	0.05	65.23	21.74	0.78
D	3	168.98	56.33	2.44	54.40	18.13	0.70	0.76	0.25	0.01
Error	3	69.30	23.10	\	77.17	25.72	\	83.97	27.99	\

(Note: The critical value of *F* (3,3) at the significance level of 80% is 2.93, at the significance level of 75% is 2.35, and at the significance level of 50% is 1.00.).

TABLE 6 The UCS of slag-mud soil based geopolymer modified by different plant fibers.

Fiber type	Fiber content (wt%)	UCS (MPa)			Increase in UCS (%)		
		3 days	7 days	28 days	3 days	7 days	28 days
Control group	0	30.75	33.84	42.92	—	—	—
WF	0.5	37.68	39.49	45.91	22.54	16.70	6.97
	1.0	42.82	47.06	54.85	39.25	39.06	27.80
	1.5	45.58	51.58	58.69	48.23	52.41	36.74
JF	0.5	31.21	34.64	39.54	1.50	2.37	−7.88
	1.0	40.72	42.71	48.22	32.42	26.21	12.35
	1.5	37.95	38.17	44.95	23.41	12.79	4.73
BF	0.5	39.21	42.25	49.35	27.51	24.85	14.98
	1.0	45.62	48.89	55.39	48.36	44.48	29.05
	1.5	44.69	46.08	52.68	45.33	36.16	22.74

observation of the microscopic fiber pull-out process within the matrix remains challenging under SEM, the bonding characteristics between fibers and geopolymer matrix can be preliminarily assessed through morphological examination. Figure 10a clearly shows WF fibers pulled out from the geopolymer matrix, with matrix fragments adhering to their surfaces. In Figure 10b, fractured JF fibers are visible - their smooth surfaces remain partially embedded in the geopolymer matrix. Figure 10c displays the geopolymer matrix after BF fiber extraction, showing a flat interface with localized flaking phenomena. Based on the correlation between micro-features and macro-mechanical performance, the modification mechanisms of different plant fibers in geopolymers can be attributed to synergistic interactions between interfacial bonding characteristics and fiber structural properties. For WF (diameter <10 μm), the fine diameter and high specific surface area significantly enhance fiber-matrix

contact. The surface-adhered C-(N)-A-S-H gel particles indicate chemical bonding or mechanical interlocking with the geopolymer matrix, enabling effective stress transfer and crack suppression. This mechanism explains its superior compressive strength improvement (36.74% increase at 1.5% dosage in 28 days). In contrast, JF (diameter >50 μm) exhibits performance deterioration due to dual factors. On the one hand, the large fibers act as stress concentrators (Zhao et al., 2025), inducing interfacial debonding (crack width >5 μm). On the other hand, the high cellulose content promotes self-degradation and interfacial weakening in alkaline environments (Suyam et al., 2024), resulting in attenuated strength gain or even negative growth (−7.88% increase at 0.5% dosage in 28 days). BF, with intermediate diameter between WF and JF, shows limited reinforcement efficiency due to its smooth surface restricting mechanical anchoring. When exceeding 1.0% dosage,

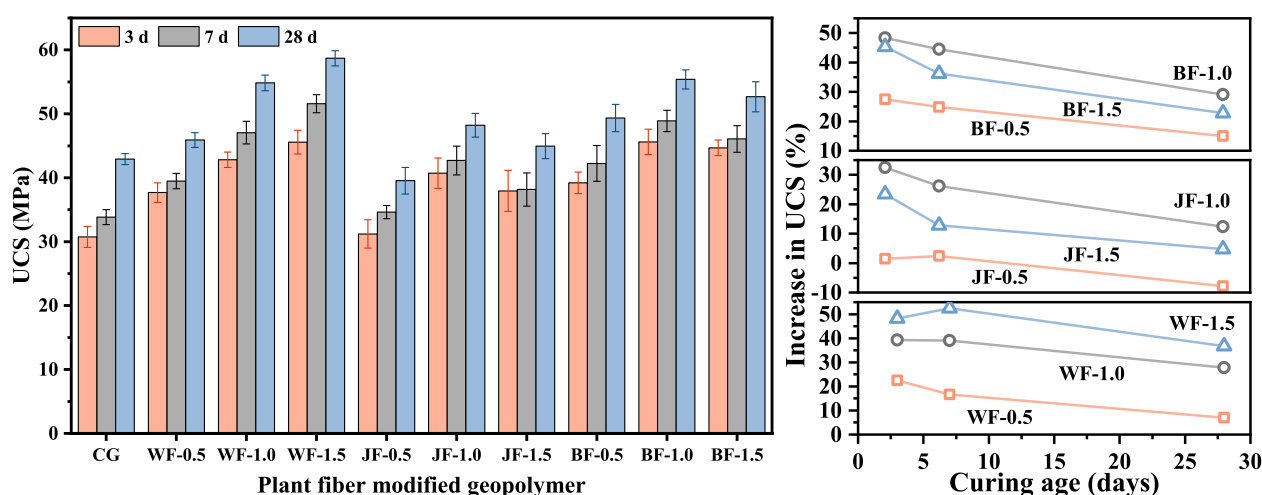


FIGURE 8
The UCS of fiber-modified geopolymer samples and their increments.

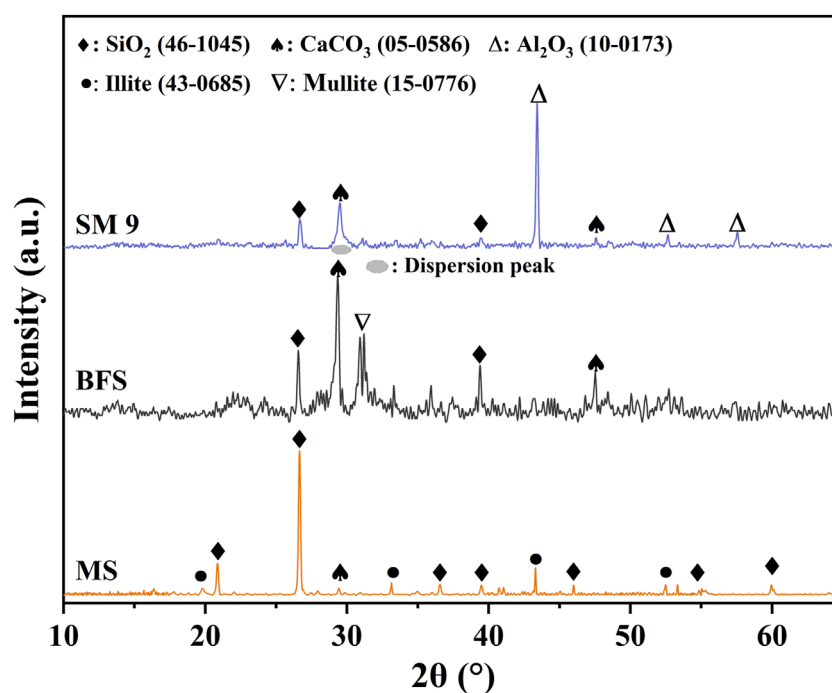


FIGURE 9
XRD patterns of raw materials and SM 9.

BF accumulation increases localized porosity, leading to reduced strength enhancement.

This analysis elucidates the mechanisms of plant fiber-modified geopolymers and provides optimized dosage recommendations. However, two critical technical challenges require further investigation: 1) improving alkali resistance of plant fibers

through surface modification or hybrid treatments, and 2) developing graded-size dosage processes to enhance reinforcement efficiency while mitigating pore formation. Addressing these aspects will advance the practical application of plant fibers in sustainable geopolymer reinforcement technologies.

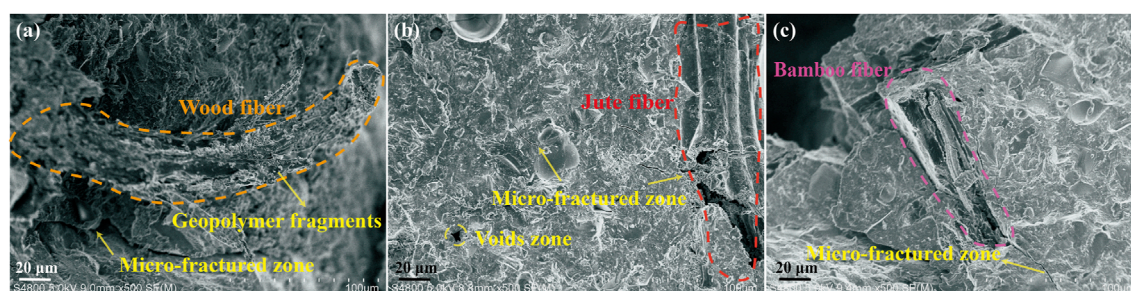


FIGURE 10
SEM micro image of fiber-modified geopolymer samples (a) WF; (b) JF; (c) BF.

4 Conclusion

The resource utilization of MS is a topic that has been neglected for a long time. This study proposes an *in situ* MS stabilization technology based on a BFS-MS geopolymer system, with key parameters—activator modulus, alkali content, water-to-solid ratio, and MS replacement rate—optimized through orthogonal experiments. Additionally, the effects of plant fiber type and dosage on the mechanical properties of geopolymers were investigated. The main conclusions are as follows.

- (1) The significance ranking of factors affecting the early-age (3-day) strength of BFS-MS geopolymer was: D (mud soil replacement rate) > A (SS modulus) > C (water-solid ratio) > B (SS alkali content). In contrast, the influence on long-term (28-day) strength followed a different order: C > A > B > D. While higher level of Factor D significantly inhibited early strength development, it showed negligible negative effects on the ultimate 28-day strength.
- (2) For the BFS-MS precursor system, the optimal SS modulus is 1.7, and the alkali content is 0.2. These parameters ensure high ion exchange efficiency and alkaline depolymerization of Si, Al, and Ca precursors, supporting both high early stage strength and sustained strength development during later curing phases. The BFS-MS geopolymer under the optimal ratio of 28 days can reach 43.56 MPa.
- (3) A moderate water supply facilitates ion exchange and reactions without inducing significant drying shrinkage. The optimal water-to-solid ratio in this study is 0.5. Within a specific range, the MS replacement rate does not markedly affect long-term strength. When the MS replacement rate was 0.3, the materials achieved 85.7%, 90.0%, and 99.5% of the original strength at 3, 7, and 28 days respectively, demonstrating excellent potential for engineering applications.
- (4) At 1.0% dosage, WF, JF and BF enhanced the 28-day compressive strength by 27.80%, 12.35% and 29.05% respectively. Furthermore, JF induces stress concentration due to agglomeration, resulting in a 7.88% strength reduction at 0.5% dosage and 4.73% improvement even at 1.5% dosage.
- (5) Microscopically, WF's small diameter and high specific surface area maximize fiber-matrix contact. In contrast, JF's large size and poor dispersion trigger interfacial

debonding and stress concentration, degrading strength. BF's intermediate diameter and smooth surface limit mechanical anchoring, yielding lower reinforcement efficiency than WF. While this study provides preliminary investigation into the mechanical properties of PF-modified geopolymers, further research on hybrid fiber reinforcement and long-term durability, along with field application studies, remains essential for material optimization and practical implementation.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

ZZ: Writing – review and editing, Writing – original draft. DC: Writing – original draft. YZ: Writing – original draft. JL: Writing – original draft. KZ: Writing – original draft, Writing – review and editing. HL: Writing – review and editing.

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Conflict of interest

Authors ZZ and DC were employed by China Communications Third Shipping Engineering Bureau Co., Ltd. and Ninth Engineering Company, CCCC Third Harbor Engineering Co., Ltd. Authors YZ and JL were employed by Ccid Urban Construction (Chongqing) Co. Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial

relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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