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ORIGINAL ARTICLE

Study on the Mixing Properties of Bamboo Fiber and Loose Soil

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Abstract

Slope stability is crucial for geotechnical safety. This study evaluates bamboo fiber (BF) as a sustainable reinforcement for loose soils, analyzing the effects of BF content and clay proportion on shear strength. Direct shear tests showed that BF enhances cohesion (2.2-fold increase to 6.37 kPa) and the internal friction angle (48% improvement to 37.7°), with an optimal clay content of 16%. Synergistic interactions between BF and micro-clay particles were quantified via SEM, supporting a proposed micromechanical model for shear failure. These findings demonstrate BF's efficacy in slope stabilization, offering eco-friendly solutions for embankments and tailings dams.

Keywords: Bamboo fiber, Soil reinforcement, Shear strength

Introduction

The stability of slopes plays a crucial role in safeguarding life and property, particularly prominent in the construction of roadbeds, tunnels, and bridges [1]. In recent years, accelerated urbanization has elevated slope stability to a critical issue requiring urgent exploration and effective solutions in geotechnical engineering. Currently, there is considerable attention focused on the performance of geotechnical engineering materials, particularly in soil improvement techniques. The current methods for soil improvement primarily include physical, chemical, and biological approaches. Physical methods involve adding materials with certain strength to the soil to enhance its tensile and compressive properties [2]; chemical methods improve soil mechanical properties by adding chemical materials that react with the soil [3]; and biological methods utilize microorganisms to alter the physical and chemical properties of the soil, thereby enhancing its engineering performance [4].

In recent years, numerous scholars have employed physical, chemical, and biological methods to improve soil. In terms of physical methods, Arabani M mixed wheat fiber and nano-bentonite [5], palm fiber into the soil as experimental materials; Zachariah P.J. used sugarcane bagasse fiber as a reinforcing material for sandy gravel soil [6]; Qihong Y utilized plant roots as soil reinforcement material [7]; and Ramkrishnan R employed sisal fiber to strengthen soil [8]. These studies found varying degrees of improvement in soil's compressive and shear strength indicators. In chemical methods, Srijan added Portland cement and lime as chemical materials to soft soil, effectively improving soil strength [9]; Chen L.H. employed chemical grouting to reinforce the soil around bridge abutments, enhancing its compressive properties [10]; and Yuxin W used a chemical method involving urea-induced calcium carbonate precipitation for foundation repair and reinforcement [11]. In biological methods, Fatehi H added casein and sodium caseinate biopolymers extracted from milk to sandy soil to study their effects on the mechanical properties of the soil [12]; Haystead J and Surabhi J researched denitrifying microorganisms in soil reinforcement, primarily through their enzymes and metabolic activities to precipitate carbonate minerals [13].

Regarding slope loose soil reinforcement, artificial excavation or chemical methods (commonly cement mixing for reinforcement) are frequently used [14]. However, chemical methods are costly, alter soil properties, contaminate groundwater and soil environments, and lack environmental friendliness [15]; meanwhile, biological methods are difficult to control and may result in suboptimal reinforcement effects [16]. Among physical methods, soil improvement materials mostly focus on glass fibers, sisal fibers, sugarcane bagasse, palm fibers, wheat fibers, etc. [17], while research on bamboo fibers is relatively scarce, especially in loose soil reinforcement. The reinforcement effects and bonding mechanisms between loose soil and bamboo fibers remain unexplored. Therefore, this paper selects bamboo fibers, a common plant fiber material in nature, as an improvement material for slope loose soil. Bamboo fibers are characterized by high tensile strength, durability after pretreatment, lightweight environmental friendliness, and ease of acquisition. Through direct shear tests, this paper studies the mechanical properties and interaction mechanisms of bamboo fibers in reinforcing slope loose soil and analyzes the soil's microstructure using scanning electron microscopy. The research findings can provide theoretical references for road slopes, building slopes, tailings dams, artificial soil piles, and other engineering projects.

2. Materials and Preparation

2.1 Raw Materials

The core materials of this study comprise bamboo fiber (BF) and loose slope soil (S).

Loose soil samples (S) were collected from highway slopes in southwestern China and underwent water washing, drying, grinding, sieving, and other procedures to determine their particle size distribution. The particle distribution results are as follows: 5.25% for particles below 0.075 mm, 16.78% for 0.075-0.25 mm, 32.1% for 0.25-0.5 mm, 58.71% for 0.5-1 mm, 87.26% for 1-2 mm, 93.51% for 2-5 mm, and 100% for particles above 5 mm in cumulative percentages.

Basic physical property tests on the loose soil samples were conducted according to the "Specifications for Soil Test for Highway Engineering" (JTGD40-2007, China). The results showed a liquid limit of 36.5%, a plastic limit of 23%, a plasticity index of 13.5%, an optimum moisture content of 21%, and a maximum dry density of 1.722 g/cm³.

Bamboo fibers (BF) were derived from Moso bamboo in Sichuan, China. Prior to use, they underwent pretreatment processes including screening, impurity removal, chemical treatment, drying, and size control. The pretreatment steps are as follows: (1) Screening and impurity removal, following the standards of ISO 22157-1:2004 (Physical and mechanical properties testing of bamboo materials). Three- to five-year-old Moso bamboo with uniform diameters and free of pests and diseases was selected. The bamboo green and bamboo yellow were mechanically stripped, retaining the bamboo fiber bundles. A high-pressure water gun (pressure ≥ 5 MPa) was used to wash the fiber surface to remove lignin and hemicellulose residues [18]. (2) Chemical pretreatment, referring to ASTM D2765 (Standard Test Method for Chemical Modification of Fibers). The fibers were soaked in a 5% NaOH solution at 25°C for 24 hours, neutralized to a pH of 7.0, rinsed, surface-grafted with 3-aminopropyltriethoxysilane (APTES, concentration of 1%), and dried at 60°C [19]. (3) Drying and size control, according to ASTM D1776 (Standard Practice for Conditioning Textiles for Testing). The fibers were placed in a constant temperature drying oven (60°C ± 2°C) to dry until the moisture content was ≤8% (determined by the mass loss method). A high-speed cutting machine was used to cut the fibers to the target length (20–30 mm), and a vibrating screen (aperture of 0.18–0.28 mm) was employed to remove overly fine or coarse fibers [20].

2.2 Material Preparation

Material Preparation: According to the experimental design, bamboo fiber and test soil samples were accurately weighed. The bamboo fiber underwent cutting and screening processes to obtain fibers with lengths of 20-30 mm and diameters of 0.18-0.28 mm.

Mixing Procedure: The soil samples and bamboo fibers were weighed accurately to 0.1 g. The bamboo fibers were added to the soil samples, and a predetermined amount of water was sprayed onto the mixture. Manual stirring was employed to thoroughly mix the components until the bamboo fibers were uniformly distributed throughout the soil samples, with no obvious clumps or aggregations. The mixed soil samples were then sealed in plastic wrap and allowed to sit for one day and night. The mixture of bamboo fiber and loose slope soil is hereinafter referred to as the "composite mixture."

3. Experiment Design and Procedures

3.1 Experimental Design

To evaluate the reinforcement performance of bamboo fiber content on loose materials, eight experimental groups were set up, labeled as BFS-0 to BFS-7. The bamboo fiber content in these groups was varied at 0.0%, 0.5%, 1%, 1.5%, 2.0%, 3.0%, 4.0%, and 5.0%, respectively, with a consistent water content of 21% for all groups. The particle size distribution of the test soil samples is as follows: 5.25% below 0.075 mm, 11.53% between 0.075 and 0.25 mm, 15.32% between 0.25 and 0.5 mm, 26.61% between 0.5 and 1.0 mm, 28.55% between 1.0 and 2.0 mm, and 12.74% above 2.0 mm.

To assess the impact of varying clay content on the strength of the composite mixture, five additional experimental groups were set up, labeled as BFS-8 to BFS-12. In these groups, the bamboo fiber content was fixed at 2%, and the water content was maintained at 21%. The mass percentage of clay particles smaller than 0.075 mm was varied at 6%, 11%, 16%, 21%, and 26%, respectively, across the groups.

3.2 Direct Shear Test

Direct shear tests on the composite mixture were conducted using the consolidated quick shear method with the ZJ Strain-Controlled Direct Shear Apparatus manufactured by Nanjing Soil Instrument Factory, China. The test procedures adhered to the specifications outlined in the Standard Test Methods of Soil for Highway Engineering (JTGD40-2007, China).

Test Procedures:

(1) Specimen Preparation: The specimens typically had a diameter of 60 mm and a height of 25 mm. The soil samples were mixed with bamboo fibers at the preset ratio and sprayed with deionized water to achieve the target moisture content. The mixture was then divided into three layers and compacted into the shear box to the specified height, ensuring uniform fiber distribution. The specimen surface was leveled, and a porous stone and pressure cover plate were installed to avoid boundary effects.
(2) Specimen Consolidation: Vertical pressures were applied in steps of 0 kPa → 50 kPa → 100 kPa → 200 kPa → 300 kPa → 400 kPa, with a load interval of 1 minute at each level. Consolidation was considered stable when the vertical deformation was ≤0.005 mm per hour. Vertical pressures were applied using a lever or pneumatic system. Initial vertical deformations were recorded and measured every hour until the stability criterion was met. Upon consolidation, the vertical displacement sensor was locked.
(3) Specimen Shearing: The shear rate was set at 0.8 mm/min. The shear device was activated to apply horizontal displacement at a constant rate. Shear displacement and shear force were continuously recorded until one of the following termination criteria was met: a decrease of ≥20% in shear stress after the peak value or a shear displacement reaching 15% of the specimen diameter (e.g., 9 mm). Shear stress-displacement curves were plotted to determine peak and residual strengths.

Quality and Error Control: The number of parallel specimens for the same test group was ≥3, with data deviation ≤10%. The shear box and porous stones were regularly calibrated to avoid friction errors. Before testing, the accuracy of force and displacement sensors was verified (error ≤±1%). Laboratory temperature and humidity were controlled at 20±2°C and RH 50±5%, respectively, to prevent fluctuations in soil moisture content. After shearing, the failure surface morphology of the specimens was inspected to exclude abnormal data.

4. Experiment Results and Analysis

4.1 Experiment Results

In the direct shear test, we recorded the vertical pressure and the dial gauge readings of the load cell. The shear stress was calculated using the formula $\tau = CR/A * 10$, where C represents the calibration coefficient of the load cell (1.471 N/0.001 mm), R represents the dial gauge reading of the load cell (0.01 mm), and A represents the test area (30 cm^2). The shear stresses under different vertical pressures were calculated, and the results are presented in Table 1.

In the direct shear test to investigate the effect of varying clay content on the strength of the composite mixture, the calibration coefficient of the load cell and the test area in the shear stress calculation formula remained constant. The calculation results are also presented in Table 1.

Table 1. Shear displacement and strength of each test group under different vertical pressures

Groups	Vertical Pressure=100kN		Vertical Pressure=200kN		Vertical Pressure=300kN		Vertical Pressure=400kN	
	Displacement (mm)	Stress (kPa)	Displacement (mm)	Stress (kPa)	Displacement (mm)	Stress(kPa)	Displacement (mm)	Stress(kPa)
BFS-0	0.135	6.62	0.243	11.92	0.321	15.74	0.431	21.13
BFS-1	0.175	8.58	0.251	12.31	0.412	20.20	0.545	26.72
BFS-2	0.215	10.54	0.331	16.23	0.432	21.18	0.592	29.03
BFS-3	0.236	11.57	0.420	20.59	0.512	25.11	0.651	31.92
BFS-4	0.260	12.75	0.457	22.41	0.620	30.40	0.705	34.57
BFS-5	0.263	12.90	0.450	22.07	0.630	30.89	0.712	34.91
BFS-6	0.266	13.04	0.461	22.60	0.615	30.16	0.728	35.70
BFS-7	0.262	12.85	0.457	22.41	0.621	30.45	0.718	35.21
BFS-8	0.243	11.92	0.338	16.57	0.535	26.23	0.712	34.91
BFS-9	0.252	12.36	0.356	17.46	0.587	28.78	0.758	37.17
BFS-10	0.256	12.55	0.410	20.10	0.642	31.48	0.771	37.80
BFS-11	0.247	12.11	0.371	18.19	0.598	29.32	0.762	37.36
BFS-12	0.231	11.33	0.347	17.01	0.549	26.92	0.725	35.55

4.2 Analysis of Test Results under the Influence of Bamboo Fiber Content

Table 1 presents the shear stress values of different samples (BFS-0 to BFS-7) under varying vertical pressures, clearly reflecting the shear stress magnitude of each sample at specific pressures. However, these data points do not align linearly but exhibit a certain degree of dispersion. Despite this dispersion, the data points still demonstrate a discernible trend.

To enhance the accuracy and reliability of the test results and address data dispersion, a linear fitting method was utilized to smooth the discrete data, resulting in a linear relationship between shear stress and vertical pressure for each sample. All fitting curves conform to a linear function of the first degree, as illustrated in Figure 1. According to Coulomb's theorem, the slope of the fitting curve represents the internal friction angle, and the intercept represents the cohesion. These two indicators constitute the shear strength parameters of the composite mixture.

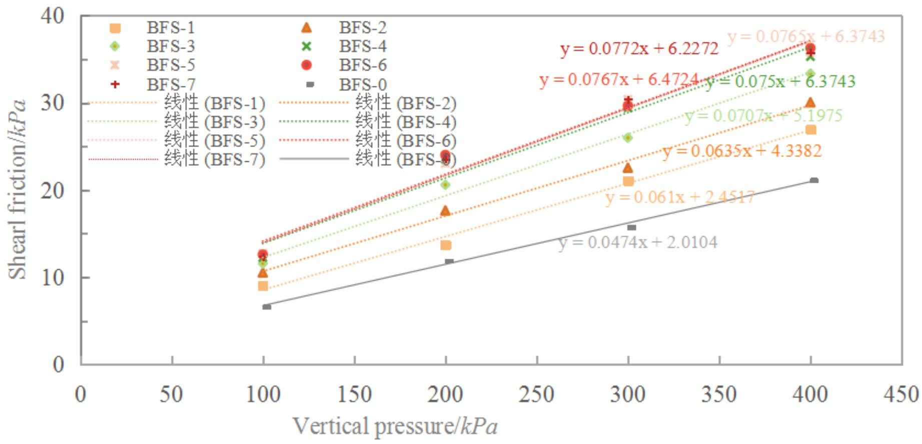


Figure 1 Fitted Curve of Experimental Results for Different Fiber Content Effects

The fitting results indicate that the slopes for Groups BFS-0 to BFS-7 are 0.0474, 0.061, 0.0635, 0.0707, 0.075, 0.0765, 0.0772, and 0.0767, respectively, while the intercepts are 2.0104, 2.452, 4.34, 5.197, 6.374, 6.374, 6.472, and 6.227. Both the intercepts and slopes for

Groups BFS-1 to BFS-7 are significantly greater than those for Group BFS-0, indicating significant enhancements. This suggests that bamboo fiber addition significantly enhances the strength of loose materials.

To further examine the reinforcement effect of bamboo fiber content on loose soil, Figure 2 graphically represents the relationship between cohesion and internal friction angle, two key soil strength indicators, and varying bamboo fiber content based on linear fitting results from Groups BFS-0 to BFS-7.

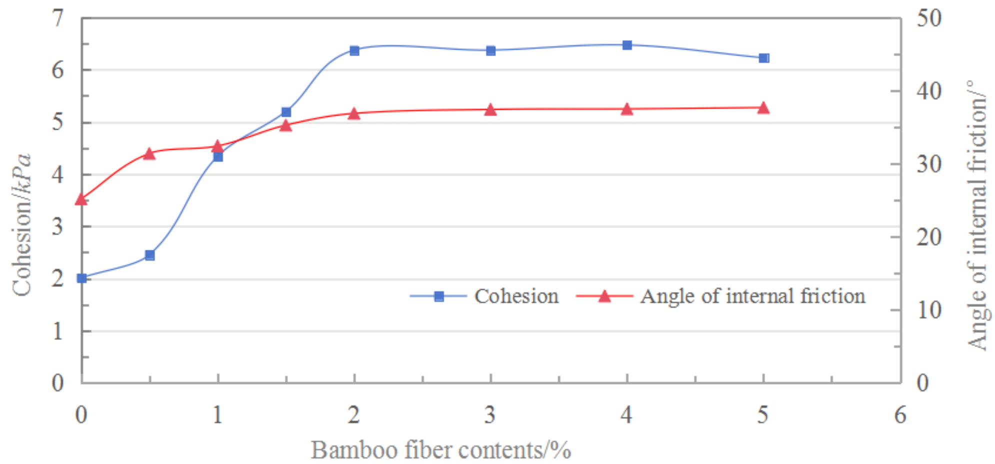


Figure 2 Relationship between Strength Indices of the Mixture under the Influence of Bamboo Fiber Content

The data in Figure 2 reveals an overall upward trend in cohesion with increasing bamboo fiber content. Group BFS-0 exhibits the lowest cohesion, with Groups BFS-1 to BFS-7 showing significant increases. Notably, cohesion increases sharply between 0.5% and 2% bamboo fiber content, reaching a 2.2-fold increase. However, cohesion slightly decreases when fiber content exceeds 2%, indicating a minor weakening effect.

Similarly, the internal friction angle increases with bamboo fiber content. Group BFS-0 has the lowest angle at 25.2°, while Group BFS-7, with 5.0% fiber content, has the highest at 37.7°, marking a 48% increase. The growth rate accelerates between 1% and 2% fiber content but decelerates thereafter.

Overall, bamboo fiber positively enhances soil shear strength characteristics. This is evident in improved macro-mechanical properties and reveals micro-level interactions between bamboo fiber and soil structure. By reconstructing soil structure, bamboo fiber provides reinforcement, achieving physical connection with soil particles. However, excessive fiber content may slightly weaken cohesion due to limited bonding particles. In conclusion, within a specific range, cohesion and internal friction angle increase; beyond this, there is a slight weakening trend.

4.3 Analysis of Test Results under Varying Clay Content

Table 1 presents the shear stress values of samples with varying clay contents (BFS-8 to BFS-12) under different vertical pressures, exhibiting a discernible trend despite some dispersion. To address this, a linear fitting method was applied to the data, yielding linear functions depicted in Figure 3.

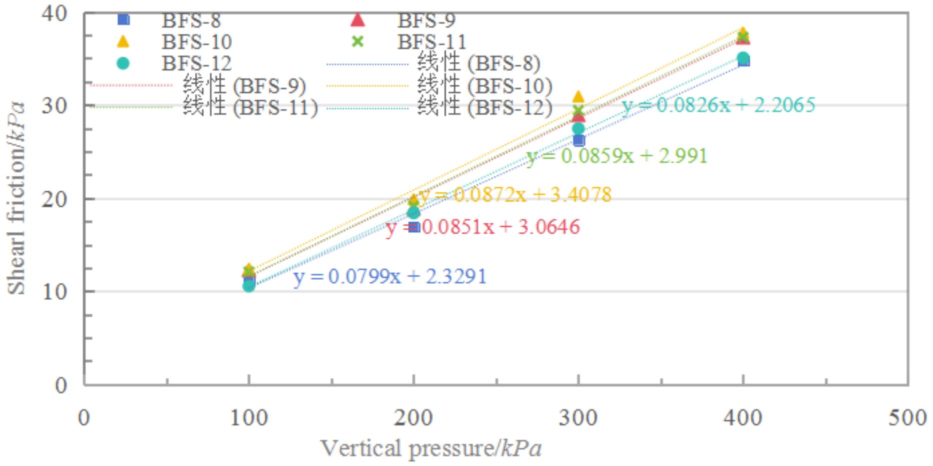


Figure 3 Linear Fitting Results under the Influence of Clay Content

A deeper analysis, based on the linear fitting results, illustrates the relationship between soil strength indicators (cohesion and internal friction angle) and clay content in Figure 4. As clay content increases from 6% to 16%, both cohesion and internal friction angle gradually rise, albeit with decreasing growth rates. Peak cohesion is observed at 16% clay content, beyond which both cohesion and internal friction angle decrease.

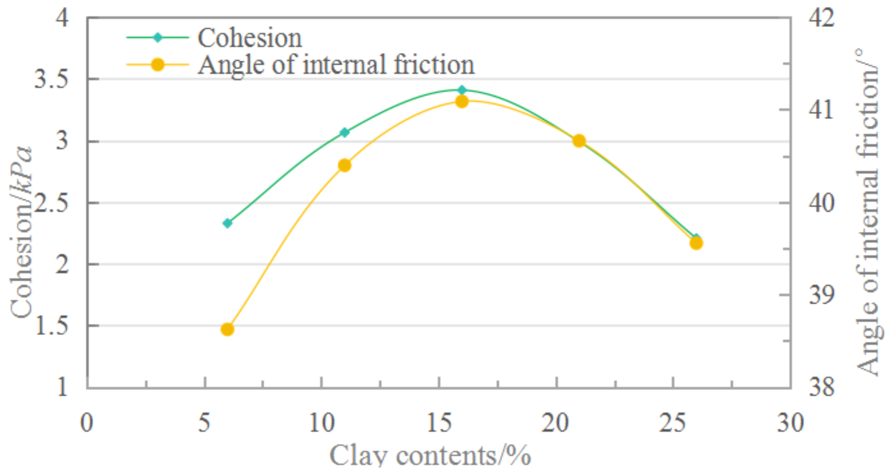
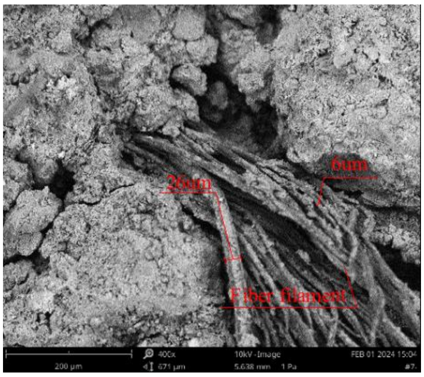


Figure 4 Strength Variation Diagram under the Influence of Clay Content

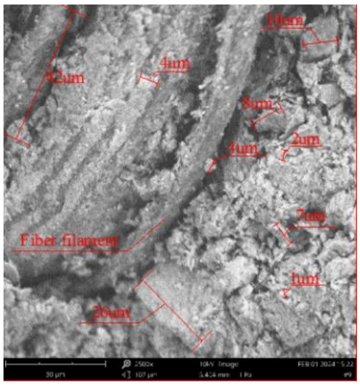
The influence of clay content on shear strength follows these laws: At lower clay contents, the mixture's shear strength enhances due to improved bonding between bamboo fibers, soil particles, and clay particles. At a critical clay content, the mixture reaches peak strength, forming an optimal structural system. Beyond this point, excessive clay reduces friction and bite force between particles, weakening the mixture's shear strength. This variation can be divided into three stages: joint reinforcement, optimal strengthening, and soil weakening.

5. Microscopic Morphology Analysis

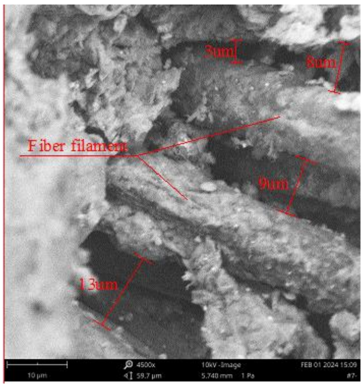
To gain insights into the characteristics of soil particle distribution, pore structure, and bamboo fiber composition during shear failure, and to elucidate macroscopic mechanical behaviour, a scanning electron microscope (SEM) (Phenom ProX, Phenom World, Netherlands) was employed to observe the micromorphology of sheared specimens.



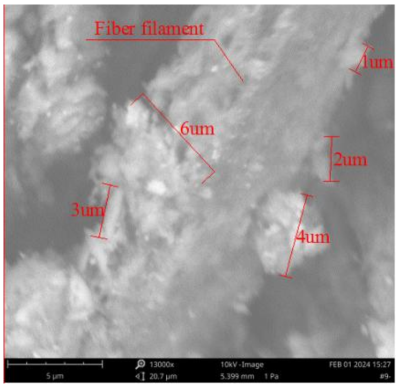
(a) 400x magnification image



(b) 2500x magnification image



(c)4500x magnification image



(d) 12000x magnification image

Figure 5 Scanning Electron Microscope Image

SEM images revealed distinct features: At 400x magnification, bamboo fiber bundles comprised multiple individual fibers, with diameters ranging from 6um to 26um (Figure 5(a)). At 2500x, soil particles of varying shapes and sizes were tightly bound, forming a porous surface structure, with smaller particles (4-42um) near the fibers (Figure 5(b)). At 4500x, post-shear displacement of fibers and soil particles was evident, with pore sizes of about 13um and fiber spacing of about 9um, indicating pore formation due to clay particle displacement (Figure 5(c)). Soil particle residues on fiber surfaces, with irregular shapes and sizes, suggested strong interactions during pullout, leaving scratches and wear marks on the fibers.

At 12000x magnification, the fiber surface exhibited a concave-convex morphology, providing conditions for clay binder embedding, with clay particle diameters on the fiber surface ranging from 2-6um (Figure 5(d)). The SEM images also showed a tight bonding interface between bamboo fibers and soil, forming an "anchoring" structure, enhancing physical connection and increasing contact area and friction.

Based on these observations, a structural model of the mixture and its failure was established,As shown in Figure 6, indicating that bamboo fibers and bulk materials are connected primarily through micro-clay particles, with a higher concentration near the fibers. Direct shear test results validated this model, showing that an increase in clay content strengthens bonding during the joint reinforcement stage, reaches optimal strength when clay content is matched with fiber and soil particle quantities, and weakens the mixture during the soil weakening stage due to excessive clay particles reducing friction and support.

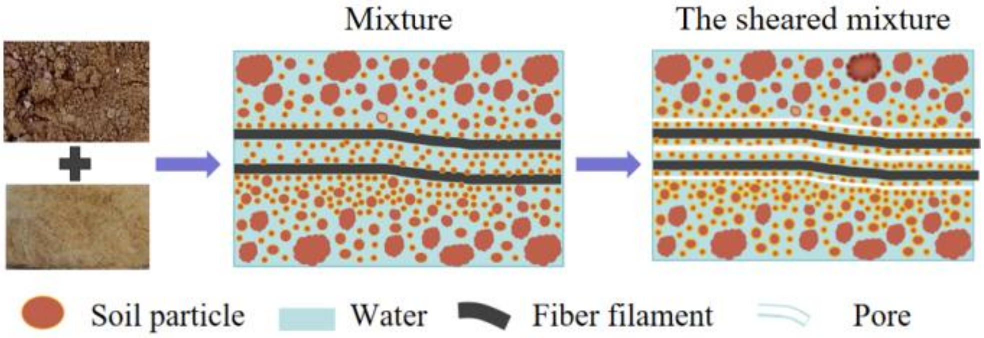


Figure 6 Structure and Failure Model of the Composite Mixture

In summary, micro-clay particle distribution significantly impacts the shear strength of the composite mixture, with an optimal amount enhancing strength but excessive amounts weakening it.

6. Conclusions

The research indicates that BF can significantly enhance the cohesion (with a 2.2-fold increase) and internal friction angle (with a 48% improvement) of loose soils. Meanwhile, an optimal amount of clay particles can strengthen the strength, whereas an excess amount leads to a reduction in strength. The BF and loose materials are primarily interconnected through micro-clay particles, with a greater number of micro-clay particles found in proximity to the BF. These findings provide theoretical support for slope engineering applications, such as highway embankments and tailings dams.

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