

## Article

# Strength and Micro-Mechanism of Guar Gum–Palm Fiber Composite for Improvement of Expansive Soil

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## Abstract

This study investigates the improvement effect and micro-mechanism of guar gum and palm fibers, two eco-friendly materials, on expansive soil. The study uses disintegration tests, unconfined compressive strength tests, triaxial compression tests, and SEM analysis to evaluate the enhancement of mechanical properties. The results show that the guar gum–palm fiber composite significantly improves the compressive and shear strength of expansive soil. The optimal ratio is 2% guar gum, 0.4% palm fiber, and 6 mm palm fiber length. Increasing fiber length initially boosts and then reduces unconfined compressive strength. Guar gum increases unconfined compressive strength by 187.18%, further improved by 20.9% with palm fibers. When fiber length is fixed, increasing palm fiber content increases and then stabilizes peak stress and shear strength (cohesion and internal friction angle), improving by 27.30%, 52.1%, and 12.4%, respectively, compared to soil improved with only guar gum. Micro-analysis reveals that guar gum enhances bonding between soil particles via a gel matrix, improving water stability and mechanical properties, while palm fibers reinforce the soil and inhibit crack propagation. The synergistic effect significantly enhances composite-improved soil performance, offering economic and environmental benefits, and provides insights for expansive soil engineering management.

**Keywords:** expansive soil; guar gum; palm fiber; mechanical properties; micro-mechanism



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## 1. Introduction

Expansive soil is a special type of soil primarily composed of clay minerals such as montmorillonite, which have strong hydrophilic properties. It exhibits significant characteristics of swelling when absorbing water and shrinking when losing water. In construction and infrastructure development, the presence of expansive soil can lead to a series of serious foundation problems. Especially in seasons or climate conditions with significant moisture variation, the swelling and shrinkage of expansive soil can cause foundation instability, resulting in issues such as uneven settlement, cracks, and structural damage to buildings [1]. These changes not only pose a threat to the safety of the buildings but also bring significant repair and reinforcement costs, increasing the economic burden of the project. Therefore, studying and addressing the problems caused by expansive soil is of great importance to the stability of the construction industry and infrastructure.

Researchers in both academia and engineering have conducted extensive studies on improving the swelling and shrinkage properties of expansive soils, enhancing their

strength, and increasing their bearing capacity. The existing research can be broadly classified into two categories: physical improvement methods and chemical improvement methods. Physical improvement methods typically involve improving the engineering properties of the soil through compaction, heating, or mechanical reinforcement [2], as well as incorporating materials such as coconut shell fibers [3], glass fibers [4], etc., or using coarse granular materials like waste glass powder [5], marble powder [6], and waste tire textile fibers [7] to improve the particle grading, cohesion, and bonding of the soil, thereby enhancing its physical and mechanical properties. Chemical improvement methods primarily involve adding materials such as cement [8], sugarcane bagasse ash [9], lime, and fly ash [10] to alter the mineral composition or structure of the soil, achieving improvement.

However, despite the effectiveness of these traditional methods in certain cases, they also have some significant limitations. First, these methods tend to increase construction costs, especially when large amounts of resources and materials are required [11]. Physical treatment methods may require substantial mechanical equipment and energy consumption, further increasing the overall project costs. While chemical stabilizers can improve soil properties relatively quickly, the instability of their long-term effects is a major issue. Some chemical additives may gradually lose effectiveness over time [12], leading to the degradation of soil properties. In addition, the use of chemical stabilizers also brings some environmental issues. For example, some chemical stabilizers may cause pollution to the surrounding environment, particularly in the case of long-term, large-scale usage, potentially leaching into groundwater and affecting the quality of soil and water sources. Harmful substances in some stabilizers may have negative impacts on the ecosystem. Therefore, traditional expansive soil improvement methods, while providing short-term solutions, also expose a range of issues such as resource consumption, environmental pollution, and unstable long-term effects [13], which urgently need to be addressed in future research and applications.

In recent years, the application of eco-friendly biomaterials and natural fibers has gradually become a new trend in expansive soil improvement research, providing effective solutions for the sustainable improvement of expansive soils. To address the above issues, this study utilizes a new eco-friendly material, guar gum and palm fibers, which breaks through the limitations of traditional improvement materials, offering a more sustainable and efficient solution for expansive soil improvement. The combination of guar gum and palm fibers not only shows significant effects in improving soil structure but also opens new possibilities for soil improvement through their natural components and environmentally friendly characteristics. Guar gum, due to its natural origin, biodegradability, non-toxicity, and specific affinity for clay minerals, demonstrates significant advantages in soil stabilization [14]. Firstly, as a natural polysaccharide derived from agricultural by-products, guar gum stands in contrast to most resins, especially synthetic resins, which are typically petroleum-based products. The natural origin of guar gum gives it higher environmental friendliness and sustainability. Unlike synthetic resins, which can cause long-term pollution in the environment, guar gum does not pose such risks. Furthermore, its biodegradability and non-toxicity are standout features, making it irreplaceable in eco-friendly soil stabilization. Unlike synthetic resins like acrylic resins or polyacrylamide, which take a long time to degrade and may cause pollution to soil and water bodies [15], guar gum degrades quickly and non-toxically, thereby reducing its negative impact on the environment. Another important characteristic of guar gum is its high viscosity and strong affinity for clay minerals, especially its ability to form hydrogen bonds with clay minerals such as montmorillonite and water molecules [16]. This enhances the cohesion of soil particles and improves moisture retention. This property makes guar gum particularly effective in treating expansive soils and other special soils, a benefit that most synthetic

resins cannot match. Additionally, guar gum offers significant cost-effectiveness. As an agricultural byproduct, its price is relatively low [17], around 1.5–2 USD per kilogram, and it is widely available worldwide. In contrast, many synthetic resins are more expensive, such as acrylic resins, which cost 3–5 USD per kilogram, and their production processes may result in a larger carbon footprint.

Finally, the temperature and pH stability of guar gum allows it to maintain effectiveness under extreme environmental conditions, enabling it to function stably in alkaline environments and under significant temperature fluctuations [18]. In contrast, many synthetic resins are prone to hydrolysis or loss of viscosity under these conditions [15]. Therefore, guar gum has a distinct advantage in soil stabilization applications, especially in situations requiring adaptation to environmental changes. In conclusion, guar gum, with its natural origin, biodegradability, affinity for clay, low cost, and stability, is an ideal material for soil stabilization.

The application of palm fiber in soil improvement also offers significant advantages. First, palm fiber has high tensile strength and corrosion resistance, providing essential structural support to the soil [19], thereby significantly enhancing its compressive strength and crack resistance. Secondly, palm fiber effectively improves the cohesion of the soil, especially when combined with guar gum. The rough surface of the palm fiber allows the guar gum gel to penetrate the fiber's micropores, forming a "fiber–gel–soil particle" composite interface [20], thus enhancing the mechanical interlocking between the palm fiber and the soil, further improving the soil's mechanical properties. Additionally, as a natural material, palm fiber is biodegradable, non-toxic, and environmentally friendly. Compared to some synthetic fibers, palm fiber has a lower negative impact on the environment [21], aligning with the principles of environmental protection and sustainability. Finally, palm fiber is cost-effective and widely available, helping to reduce the cost of soil improvement and offering high value for money, particularly in soil stabilization applications. Palm fiber is rich in lignin (>30%), and its degradation rate in humid alkaline soils is 40% lower than that of sisal (cellulose > 60%) [20], ensuring long-term reinforcement effectiveness. Studies have shown that both guar gum and palm fiber exhibit positive effects in improving the properties of expansive soil. For example, Hamza et al. [14] found through UCS and CBR tests that as the guar gum content and curing time increased, the UCS and CBR values of the expansive soil significantly improved. Guar gum can form a hydrogel, which covers the pores and enhances the cementing effect of the soil, thus effectively reducing the swelling and shrinkage of the soil and improving its strength. Research by Keshav et al. [22] also showed that when the guar gum content reached 1.5%, the soil strength increased by 100%, further validating the effectiveness of guar gum as an eco-friendly additive. Vydehi et al. [23] found that both guar gum and xanthan gum significantly improved the unconfined compressive strength (UCS) and consolidation characteristics of expansive soil at different dosages. Other studies have also shown that the improvement effect of guar gum on expansive soil increases with the dosage [24], and it can effectively improve the soil's compressibility and anti-disintegration properties [16]. Additionally, the inclusion of palm fiber also significantly improves the strength, ductility, and energy absorption capacity of the soil [17]. A review by Medina-Martinez et al. [20] pointed out that the appropriate addition of natural fibers can significantly improve the shear strength of expansive soils.

Although the above studies have demonstrated that the use of guar gum or natural fibers alone can effectively improve the physical and mechanical properties of expansive soils, a single improvement method has certain limitations. Therefore, this paper proposes a guar gum–palm fiber composite modification technique, aiming to reduce the contact between soil and water and enhance soil cohesion through the gel matrix formed by the

hydration reaction of guar gum. At the same time, the reinforcing effect of palm fibers can effectively suppress crack propagation, thus providing an economic and environmentally friendly composite modification solution. First, different amounts of guar gum are added to expansive soil for disintegration and unconfined compressive strength tests to evaluate the effect of guar gum on the water stability and compressive performance of the expansive soil and determine the optimal dosage of guar gum. Then, the best amount of guar gum and different amounts of palm fibers are incorporated, followed by unconfined compressive strength and triaxial compression tests to analyze the effect of palm fibers on the strength and deformation failure characteristics of the guar gum-modified soil, and to evaluate the improvement effect of the guar gum–palm fiber composite material on the mechanical properties of expansive soil. Finally, through micro-mechanism analysis, the modification mechanism and failure mechanism of the guar gum–palm fiber composite-modified expansive soil are revealed, providing theoretical guidance for engineering management in expansive soil areas.

## 2. Materials and Methods

### 2.1. Expansive Soil

The expansive soil used in this experiment was sourced from the third section of the engineering project located along Enhu Road (Yongwu Road–Jinlun Road) in Nanning, Guangxi. The sampling depth was approximately 2.8 m, with soil colors ranging from gray-white to brown, and a relatively high clay content. Inoue A et al., through X-ray diffraction (XRD) mineralogical analysis, found that the main mineral components of expansive soil are montmorillonite and illite [25]. The expansive soil sample is shown in Figure 1.



**Figure 1.** Expansive soil.

### 2.2. Guar Gum

Guar gum is a water-soluble polymer that appears as a milky white powder (as shown in Figure 2a). Its molecular structure is linear, as illustrated in Figure 2b, and contains hydroxyl (–OH) and carboxyl (–COOH) groups [16]. The aqueous solution of guar gum exhibits high viscosity and demonstrates excellent water resistance and stability. Its chemical structure remains stable under certain temperature and pH conditions [18].

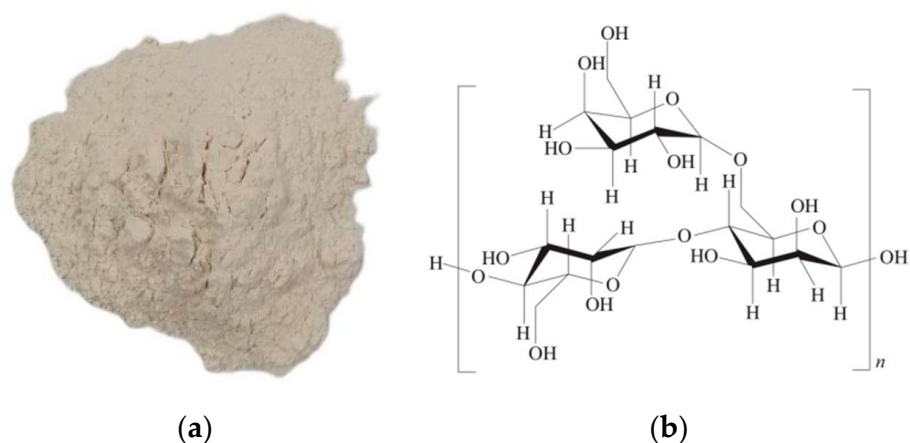


**Figure 2.** (a) Guar gum powder; (b) guar gum's molecular structural formula.

### 2.3. Palm Fiber

The palm fiber used in this study is derived from natural mountain palm fibers from Yichang, Hubei, and has a brownish color (as shown in Figure 3). The properties of the fiber are presented in Table 1. Palm fiber is known for its high toughness, corrosion resistance, and insect-repellent characteristics. Additionally, it has a high tensile strength along the grain direction [19].



**Figure 3.** Palm fiber.

**Table 1.** Physical property indexes of the palm fiber.

| Density<br>(g·cm <sup>3</sup> ) | Mean<br>Diameter<br>(mm) | Young's<br>Modulus<br>(GPa) | Tensile<br>Strength<br>(MPa) | Elongation<br>at Break<br>(%) |
|---------------------------------|--------------------------|-----------------------------|------------------------------|-------------------------------|
| 1.37                            | 0.3                      | 0.8                         | 135.2                        | 18.75                         |

### 2.4. Experimental Design

#### Sample Preparation

The soil samples used in the experiment are divided into three categories: expansive soil, guar gum-improved expansive soil (hereinafter referred to as guar gum-improved soil), and palm fiber-improved expansive soil (hereinafter referred to as composite-improved soil). Among these, the guar gum-improved soil is used to determine the optimal dosage of guar gum, defined as the mass ratio of dry guar gum to dry expansive soil. The composite-

improved soil is used to determine the optimal dosage of palm fiber, defined as the mass ratio of dry palm fiber to the soil sample (which includes both dry expansive soil and dry guar gum). The experimental design of this study is based on the “Highway Geotechnical Testing Specifications” (JTG 3430-2020) [26]. The mixing ratios in the experimental design are shown in Table 2. For simplicity, all ratios are represented using simple codes. For example, G1P0.4L3 indicates a guar gum content of 1%, a palm fiber content of 0.4%, and a palm fiber length of 3 mm. Other ratios are similarly represented.

**Table 2.** Designed mix ratios of the specimens.

| Specimen Number                      | Test Type                            | Sample Type                                                                           | Dosage of Guar Gum (G/%)           | Dosage of Palm Fiber (P/%)  | Length of Palm Fiber (L/mm)                         |
|--------------------------------------|--------------------------------------|---------------------------------------------------------------------------------------|------------------------------------|-----------------------------|-----------------------------------------------------|
| 1<br>2~6                             | Disintegration test                  | Expansive soil<br>Expansive soil + Guar gum                                           | 0<br>0.5, 1, 1.5, 2, 2.5           | 0<br>0                      | 0<br>0                                              |
| 7<br>8~11<br>12~15<br>16~19<br>20~23 | Unconfined compressive strength test | Expansive soil<br>Expansive soil + Guar gum<br>Expansive soil + Guar gum + Palm fiber | 0<br>0.5, 1, 1.5, 2<br>2 (Optimal) | 0<br>0<br>0.2<br>0.4<br>0.6 | 0<br>0<br>3, 6, 9, 12<br>3, 6, 9, 12<br>3, 6, 9, 12 |
| 24<br>25<br>26<br>27<br>28           | Triaxial compression test            | Expansive soil<br>Expansive soil + Guar gum<br>Expansive soil + Guar gum + Palm fiber | 0<br>2 (Optimal)<br>2 (Optimal)    | 0<br>0<br>0.2<br>0.4<br>0.6 | 0<br>0<br>6 (Optimal)                               |

According to the “Geotechnical Test Methods for Highway Engineering” (JTG 3430-2020) [26], in this experiment, air-dried expansive soil was crushed and sieved through a 2 mm sieve to avoid the acceleration of disintegration caused by coarse particles during the disintegration test, which could obscure the true water stability of the clay. Additionally, coarse particles may cause stress concentration or molding defects in the specimen during the unconfined compressive strength test. Water is added according to the maximum dry density ( $\rho_{d \max}$ ) and optimum moisture content ( $w_0$ ) specified in Table 1 to prepare the soil mix, and the required water amount is calculated. First, an appropriate amount of air-dried soil is placed in a mixing bowl, and guar gum is added and thoroughly mixed. Subsequently, water is gradually sprayed into the mixing bowl using a spray bottle. During the mixing process, any clumped soil samples are manually broken apart, and spraying continues until the optimum moisture content is reached. For the preparation of soil samples containing guar gum and palm fiber, the guar gum is first thoroughly mixed with the air-dried soil sample. Then, water is added to achieve 2% below the optimum moisture content. Palm fibers are added, and the mixture is thoroughly stirred again. The well-mixed soil samples are then placed in sealed bags and left to rest for 48 h for conditioning.

The disintegrated samples are compacted in layers using standard molds to form cubic samples with side lengths of 50 mm, with a compaction degree set to 90%. The samples for the unconfined compressive strength test are cylindrical, with a diameter of 50 mm and a height of 100 mm. The samples are prepared using the layer-by-layer compaction method. First, the required amount of soil is calculated based on the 90% compaction degree and added in five layers to a compaction mold. After each layer is added, a compaction hammer is used to compact the soil to the target depth. After all compaction steps are completed, the compaction mold is placed in an electric demolding machine for removal. The samples for the triaxial compression test are cylindrical, with a diameter of 39.1 mm and a height of 80 mm, and are also prepared using the layer-by-layer compaction method. The compaction procedure is repeated until the soil sample is level with the top port of the triaxial apparatus. The prepared samples are cured for 0 and 14 days. The selection of 14-day curing is consistent with the rapid stabilization characteristics of the biopolymer. According to the “Test Procedures for Stabilized Materials with Inorganic

Binders in Highway Engineering” (JTG E51-2009) [19,27] and the studies by Hamza and Vydehi [14,23], due to the fast hydration kinetics, guar gum can achieve more than 95% of its final strength within 14 days. For the samples cured for 14 days, after demolding, they were wrapped with cling film and placed in a moisture chamber for curing under a constant temperature of 20 °C.

## 2.5. Experimental Methods

To study the basic physical properties of expansive soil, free expansion rate tests, plastic limit tests, specific gravity tests, and compaction tests were conducted to investigate the fundamental physical characteristics of the expansive soil. The procedures for all tests were carried out in accordance with the “Highway Geotechnical Testing Code” (JTG 3430-2020) [26]. The following methods were used for the four basic physical experiments, along with descriptions of the test instruments:

- Free expansion rate test

The test instruments are shown in Figure 4a. According to the guidelines [26], the expansive soil is air-dried and crushed, then passed through a 0.5 mm sieve. The sieved soil is then evenly mixed. The free expansion rate is calculated using the following formula:

$$\delta_{ef} = \frac{V - V_0}{V_0} \times 100\% \quad (1)$$

where  $\delta_{ef}$  is the free expansion rate (%),  $V$  is the volume of the soil sample after it has stabilized in water (mL), and  $V_0$  is the volume of the soil sample in free pile form in air (mL).

- Plastic limit and liquid limit test

The plastic limit and liquid limit combined method is used to determine the boundary moisture content of expansive soil. The instrument used for the test is a digital soil liquid-plastic limit combined tester, as shown in Figure 4b. According to the guidelines [26], the expansive soil is air-dried, crushed, and then passed through a 0.5 mm sieve. The sieved soil is then evenly mixed. Based on the test data, a graph of the relationship between moisture content and cone penetration depth is plotted on double logarithmic coordinate paper, from which the liquid limit and plasticity index of the expansive soil are obtained.

- The specific gravity test

The specific gravity test uses the specific gravity bottle method, and the specific gravity bottle used in the test is shown in Figure 4c. Based on the test data, the specific gravity of the soil particles is calculated using the following formula:

$$G_s = \frac{m_s}{m_1 + m_s - m_2} \times G_w \quad (2)$$

where  $G_s$  is the specific gravity of the soil particles,  $m_s$  is the mass of the dried soil (g),  $m_1$  is the total mass of the bottle and pure water (g),  $m_2$  is the total mass of the bottle, pure water, and soil (g), and  $G_w$  is the specific gravity of pure water at 4 °C.

- The compaction test

The compaction test is conducted by compacting the soil sample with a compaction hammer to obtain the maximum dry density and optimum moisture content after soil compaction. The compacted sample is shown in Figure 4d. According to the guidelines [26], the air-dried expansive soil is crushed and passed through a 5 mm sieve, and the crushed soil is then thoroughly mixed evenly. The test uses the heavy compaction method, with the following dimensions of the compaction mold: an inner diameter of 10 cm, a height of 12.7 cm, and a volume of 997 cm<sup>3</sup>; the compaction hammer weighs 4.5 kg, with a drop

height of 45 cm. Based on the test data, the curve of the relationship between dry density and moisture content is plotted, from which the maximum dry density and optimum moisture content are obtained.

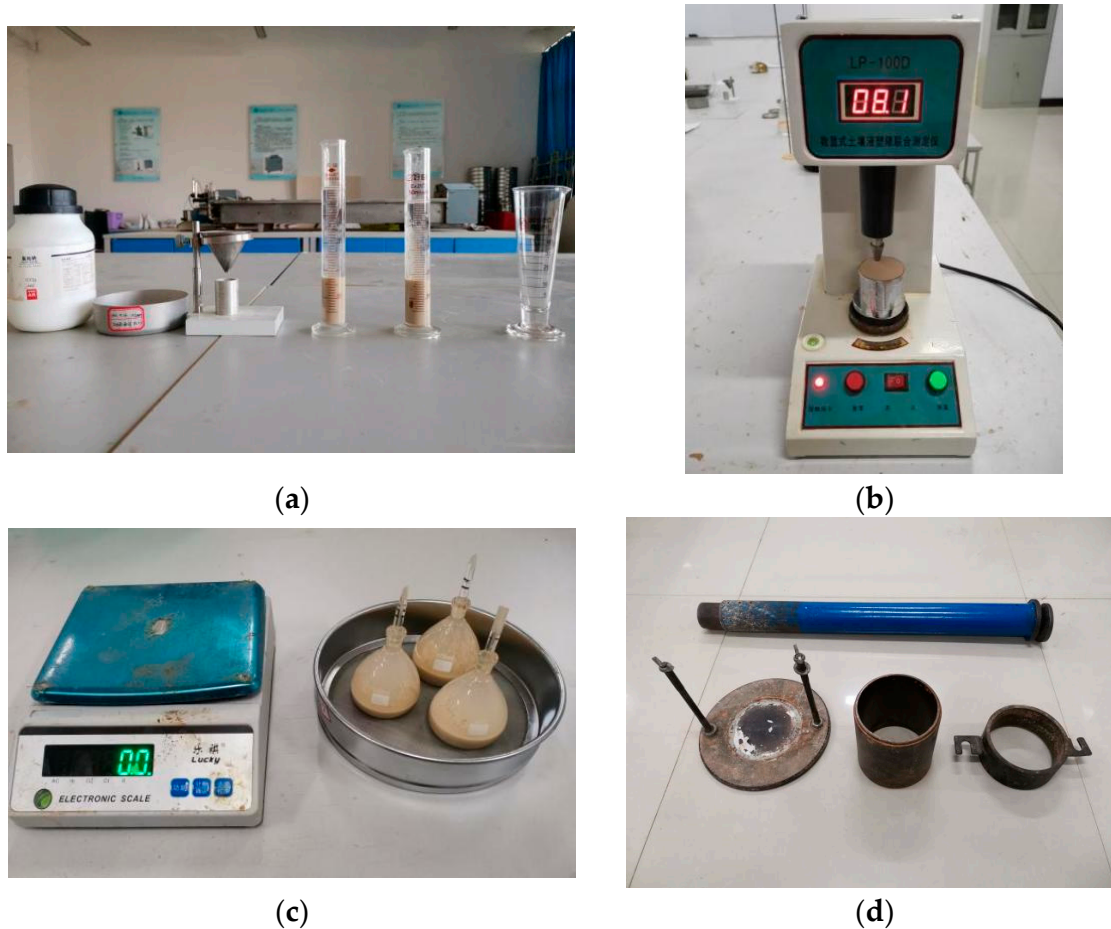


**Figure 4.** The experimental instruments used in the indoor tests. (a) The instruments used for the free expansion rate test; (b) liquid-plastic limit combined tester; (c) specific gravity test with a specific gravity bottle; (d) compaction hammer and compaction mold.

In the study of the mechanical properties and improvement methods of expansive soil, the following are the detailed steps and method descriptions for the four experiments. The instruments used in the experiments are shown in Figure 5:

- Disintegration rate test

In the specimen maintenance process, the specimen is first placed on a 10 cm × 10 cm metal mesh, which is then suspended from the hook of a force gauge using a thin string. The assembly is then submerged in a transparent glass water tank with a water level of 20 cm. During the disintegration process, the force gauge readings are automatically collected by a computer once every second, and a camera simultaneously captures images to document the state of the specimen in the water. The test is terminated when the force gauge reading drops to zero or stops changing. The disintegration rate, denoted by  $\eta$ , is used to characterize the disintegration properties of expansive soil and is calculated using the following formula:

$$\eta = \frac{m_0 - m}{m_0} \times 100\% \quad (3)$$

where  $\eta$  is the disintegration rate (%),  $m_0$  is the mass of the specimen before disintegration (g), and  $m$  is the mass of the specimen after stable disintegration (g).

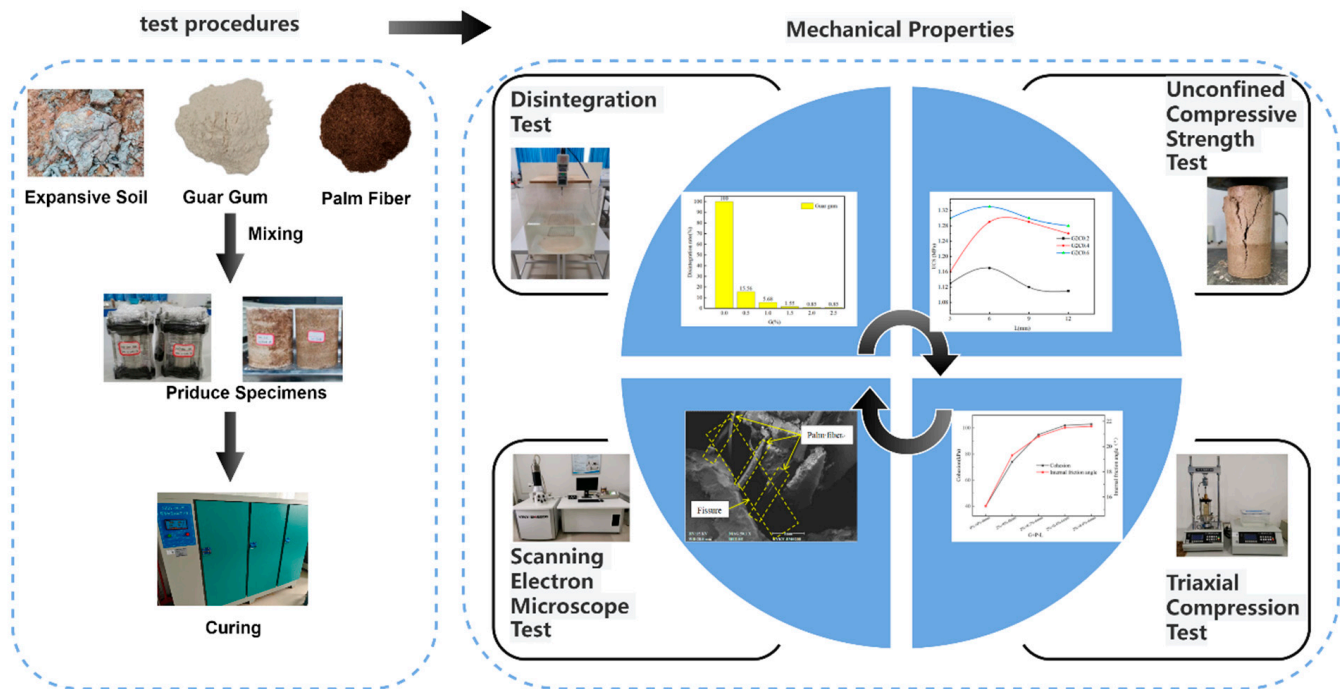


**Figure 5.** Experimental design process for expansive soil improvement.

- Unconfined compressive strength test

In this test, the XS (082) F-type universal testing machine is used, the equipment is manufactured by Xinshi Testing Equipment Co., Ltd. in Dongguan City, Guangdong Province, China, with a loading rate set at 3 mm/min, in accordance with the standard requirements [26]. This rate helps prevent moisture redistribution in expansive soils during rapid failure. During the test, when the axial stress peak appears on the stress–strain curve or the axial stress stabilizes, the strain is further applied by 3% to 5% until the test is stopped. If no peak appears on the curve or the axial stress does not stabilize, the test is stopped when the axial strain reaches 20%.

- Triaxial compression strength test

The test follows the “Test Methods of Soils for Highway Engineering” (JTG 3430-2020) [26] for consolidated undrained tests. The TSZ-2 type fully automated triaxial testing apparatus is used, the equipment is manufactured by Beijing Keheng Testing Equipment Co., Ltd. in Beijing, China. During the test, the shear strain rate is set at 0.08 mm/min as per the standard, and the saturated clay consolidated undrained (CU) test requires low-speed loading to ensure sufficient dissipation of pore water pressure during the shear process. For each soil mixture (e.g., G0P0L0, G2P0L0, G2P0.2L6, etc.), multiple specimens are tested under the three different confining pressures (100 kPa, 200 kPa, and 300 kPa). The peak deviator stress (principal stress difference,  $\sigma_1 - \sigma_3$ ) at failure for each confining pressure is recorded. A series of Mohr’s circles is then plotted using the major principal stress ( $\sigma_{1f}$ ) and minor principal stress ( $\sigma_{3f}$ ) at failure for each test. The shear strength parameters—cohesion ( $c$ ) and internal angle of friction ( $\varphi$ )—are determined by drawing the best-fit tangent line (the Mohr–Coulomb failure envelope) to these Mohr’s circles. This process is performed automatically by the data acquisition and analysis software of the triaxial apparatus.

- Scanning electron microscopy (SEM) test

The KYKY-EM6200 digital scanning electron microscope and GVC-1000 ion sputtering instrument are used for observation. The equipment is manufactured by Beijing KeYiTong

Technology Co., Ltd. in Beijing, China. First, the specimens from the disintegration, unconfined compressive strength, and triaxial compression tests are air-dried and placed on a hammering mat, then crushed using a roller. The crushed soil samples are then placed in the ion sputtering instrument for metal powder coating. Finally, the scanning electron microscope is used to observe the microstructure of the soil samples.

### 3. Result Analysis

#### 3.1. Analysis of Basic Physical Test Results of Expansive Soil

Indoor tests were conducted to determine its basic physical properties, with relevant data shown in Table 3. Based on the free expansion rate classification, the soil is categorized as medium expansive soil. According to the measured liquid limit and plasticity index, the expansive soil used in the experiment is classified as high liquid-limit clay [28]. It exhibits significant water absorption expansion and water loss shrinkage characteristics, posing notable engineering hazards. Subsequent experiments will mix the soil based on the maximum dry density and optimal moisture content obtained from the compaction test.

**Table 3.** Physical property indexes of the expansive soil.

| Liquid Limit (%) | Plastic Limit (%) | Plasticity Index (%) | Free Swelling Ratio (%) | Specific Gravity | Maximum Dry Density (g/cm <sup>3</sup> ) | Optimum Moisture Content (%) |
|------------------|-------------------|----------------------|-------------------------|------------------|------------------------------------------|------------------------------|
| 59.3             | 20.9              | 38.4                 | 75                      | 2.68             | 1.78                                     | 14.38                        |

#### 3.2. Effect of Guar Gum Content on Disintegration Characteristics of Expansive Soil

When expansive soil comes into contact with water, disintegration can lead to the collapse of the soil structure, a sharp decrease in strength, and other adverse effects, which directly impact the long-term safety of engineering projects. The disintegration test results of expansive soil modified with different guar gum contents are shown in Figures 6 and 7.

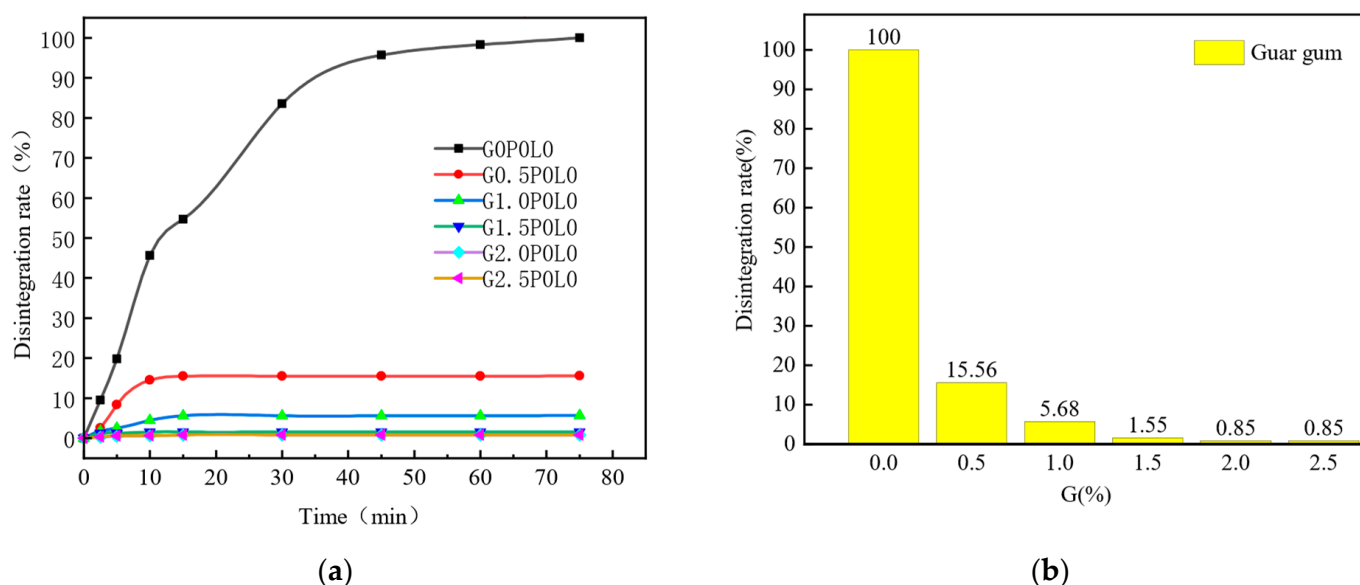


**Figure 6.** Relationship between the disintegration rate of the improved expansive soil and time, as well as dosage: (a) change in disintegration rate with time; (b) change in disintegration rate with dosage.

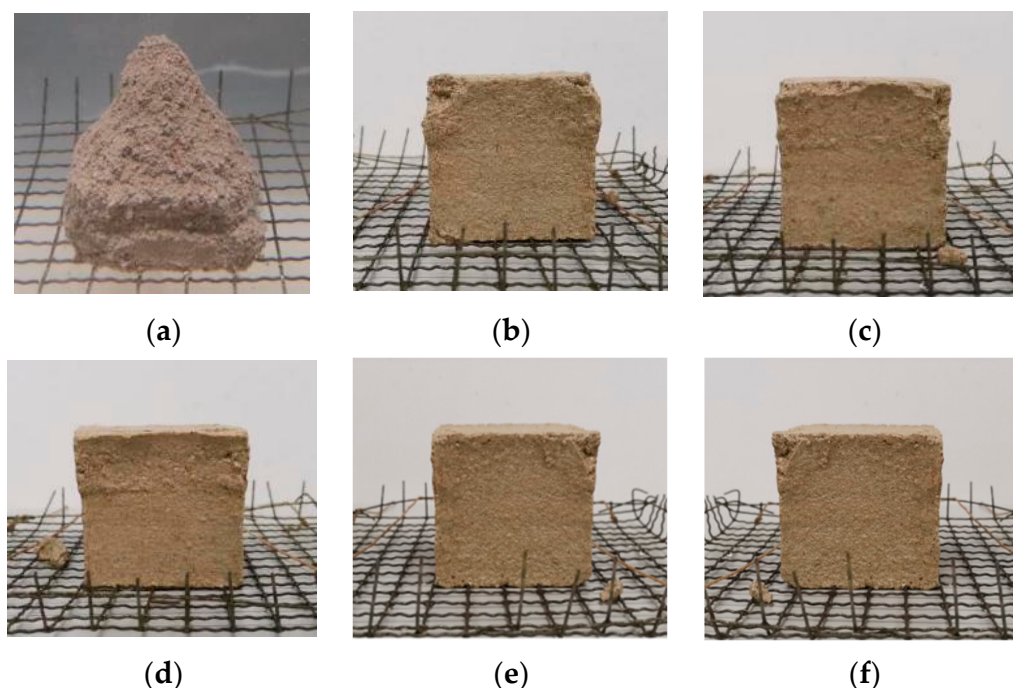


**Figure 7.** Failure morphologies of the soil samples of the expansive soil improved with different dosages of guar gum after stable disintegration: (a) G0P0L0; (b) G0.5P0L0; (c) G1.0P0L0; (d) G1.5P0L0; (e) G2.0P0L0; (f) G2.5P0L0.

As seen in Figure 6, the G0P0L0 sample exhibited a rapid disintegration rate, with a disintegration rate exceeding 90% after 45 min of static water immersion, indicating extremely poor water stability. After adding guar gum to the expansive soil, the disintegration of the soil was significantly suppressed. This is because the gel matrix generated by guar gum during the hydration reaction fills the pores between soil particles, reducing the contact between water molecules and clay minerals such as montmorillonite, thereby inhibiting the swelling and shrinking properties of expansive soil and improving its water stability. On the other hand, the gel matrix forms hydrogen bonds between soil particles. Vydehi and Moghal [23,24] discovered the above mechanism when studying the disintegration of expansive soils. This bonding effect increases the cohesion of the soil, enhancing the expansive soil's resistance to water lubrication, as further explained in Section 3.5. particularly in the G1.5P0L0, G2.0P0L0, and G2.5P0L0 samples. The disintegration rate of the modified expansive soil was significantly reduced, even to less than 5%. The disintegration stability time of these samples was relatively short, with the disintegration rate of the G2.0P0L0 and G2.5P0L0 samples being as low as 0.85%, suggesting that when the guar gum content reached 2%, the disintegration improvement effect of the expansive soil tended to saturate, and the water stability reached its optimal level.

Figure 6 shows the photographs of the samples after static water immersion to the point of disintegration stability for both unmodified soil and soil modified with different guar gum contents. As can be observed from the Figure, compared to the G0P0L0 sample in Figure 7a, the guar gum-modified soil samples showed a significant improvement in disintegration resistance. In Figure 7b, the G0.5P0L0 sample showed slight soil detachment at the top corner, with fine cracks appearing along the edges. The G1P0L0 sample in Figure 7c exhibited slight damage at the top edges and corners but was overall more intact than the G0P0L0 sample shown in Figure 7b. In Figure 7d, the G1.5P0L0 sample displayed minor soil detachment at one top corner, with no significant detachment observed at other locations, though slight deformation was present. In Figure 7e, the G2P0L0 sample only showed slight soil detachment at one top corner, and the surface of the sample after

disintegration stabilization was relatively smooth, without visible cracks. The G2.5P0L0 sample in Figure 7f appeared almost identical to the G2P0L0 sample in Figure 7e, with a smooth surface and no significant differences.

By comparing the expansive soil improved with five different dosages of guar gum, it was observed that when the guar gum content exceeded 2%, the disintegration of the samples remained almost unchanged. Therefore, in the disintegration test, the best anti-disintegration performance was achieved when the guar gum content was at the optimal ratio of 2%.

### 3.3. The Effect of Palm Fiber Content and Length on UCS

Figures 8 and 9 show the stress–strain curves for the unconfined compressive strength tests of pure soil, guar gum-modified soil, and composite-modified soil. From Figure 5, it is evident that guar gum significantly enhances the unconfined compressive strength of expansive soil. With an increase in the guar gum content, the compressive strength of the modified soil shows a noticeable improvement. When the guar gum content reaches 2%, the unconfined compressive strength of the G2P0L0 sample reaches its maximum value of 1.10 MPa, which is a 187.18% increase compared to pure soil. This is similar to the UCS values observed by Hamza et al. [14] in the improvement of similar expansive soils. This enhancement results from the bonding effect of the continuous gel film formed by guar gum on soil particles, which gives the soil a strong resistance to destruction and deformation.

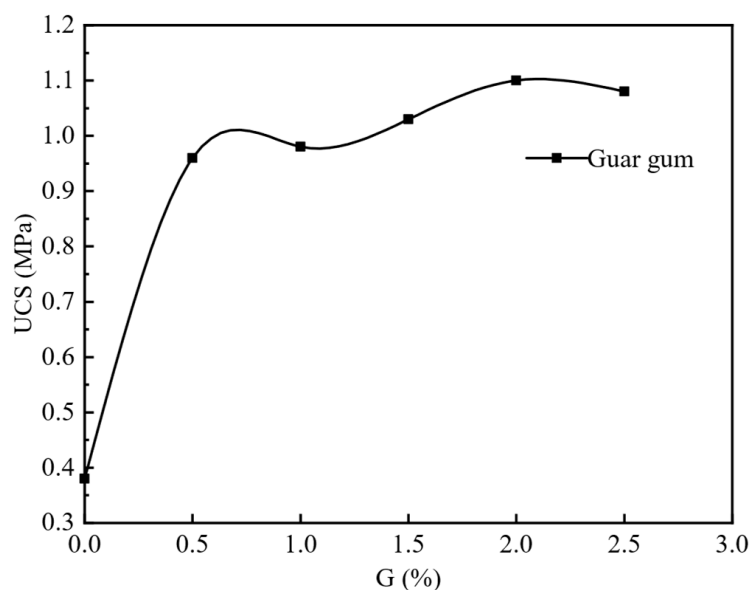


**Figure 8.** Variation curve of UCS for guar gum-modified soil specimens.

Further analysis reveals that when the guar gum content is optimized at 2%, the palm fiber content and length significantly affect the unconfined compressive strength. After comprehensive consideration, the optimal guar gum content for both the dispersion test and the unconfined compressive strength test is 2%. Therefore, in subsequent experiments, the guar gum content will be fixed at 2%. Figure 9 illustrates the variation in compressive strength for guar gum–palm fiber composite-modified soil. The results show that, with a fixed palm fiber length, as the palm fiber content increases, the compressive strength of the composite-modified soil gradually increases. Conversely, when the palm fiber content is fixed, the change in palm fiber length exhibits a trend of first increasing and then decreasing. Notably, when the palm fiber content is 0.6% and the fiber length is 6 mm, the unconfined compressive strength of the G2P0.6L6 sample reaches its maximum value of 1.33 MPa, which is a 20.9% increase compared to the G2P0L0 sample. This indicates that

the proper combination of palm fiber content and length contributes to further enhancing the compressive strength of the modified soil.

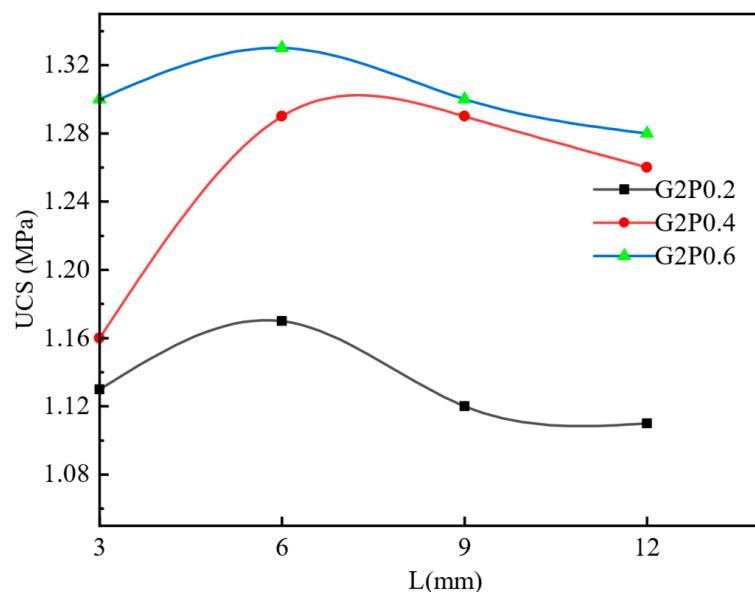


**Figure 9.** Variation curve of UCS for composite-modified soil.

The composite modification effect of guar gum and palm fiber primarily manifests in enhancing the physical structure and compressive capacity of expansive soil. Guar gum, with its strong adhesiveness, can form a network structure in the soil, enhancing the bonding force between particles. Particularly when the content is 2%, this network structure optimizes the soil's microstructure, improving stability and compressive strength. Palm fiber, as a natural fiber, effectively enhances the compressive strength of the soil by serving as a framework support to help distribute external loads. The composite modification of guar gum and coir fibers is complementary: the former enhances the bonding ability, while the latter strengthens the structural integrity through a three-dimensional fiber framework. The synergistic effect between the two materials results in an additive effect (synergy index = 1.33), leading to a 20.9% improvement in the compressive strength of expansive soils, significantly higher than the effect of a single material. Ghasemzadeh and Khattak [29,30] also observed this additive effect when incorporating both materials into soil.

However, there is an optimal incorporation amount for compressive strength improvement. Once the optimal coir fiber content is exceeded, the fibers become unevenly distributed within the soil, forming fiber clustering, which leads to localized stress concentration. This weakens the reinforcement effect, resulting in a reduction in the enhancement effect [31], as further explained in Section 3.6. Based on the above experimental results, the optimal composite-modified soil mix is determined to be 2% guar gum, 0.6% palm fiber content, and a palm fiber length of 6 mm.

#### Failure Modes of Improved Expansive Soil Samples

Figure 10a,b shows the failure morphologies of the pure soil sample, guar gum-modified soil sample, and guar gum–palm fiber composite-modified soil sample under unconfined compressive strength tests. All samples are cylindrical, with a diameter of 50 mm and a height of 100 mm. The G0C0L0 sample undergoes structural failure under axial stress, with local soil particle collapse. The surface of the sample shows deep “Y”-shaped cracks, with multiple micro-cracks appearing around the main crack, which run through the entire sample. This type of failure mode indicates that the soil structure is damaged, and the soil may be in a loose state with relatively low cohesion, allowing the formation of

large cracks. In contrast, the G2C0L0 sample shows a significant reduction in small surface cracks. The upper part of the sample maintains good overall integrity, and large cracks do not run through the entire sample but form a shear failure plane. This failure plane starts from the center of the sample and cuts diagonally along the axis to the bottom of the sample, forming a “V”-shaped failure surface with other cracks. This phenomenon suggests that the addition of guar gum primarily affects the failure mode of the sample, shifting from “Y”-shaped cracks to “V”-shaped cracks. This change is due to the improvement of the unconfined compressive strength of the soil by guar gum, indicating that guar gum alters the internal structure of the soil. The high-viscosity gel formed by the reaction between guar gum and expansive soil fills the gaps between particles and coats the surface of the soil particles, enhancing the bonding between the particles, thereby transforming the soil structure from a loose state to a denser structure. This structural change improves the overall integrity and stability of the sample, suppressing the longitudinal extension of large cracks. Under the influence of cohesion, even the small cracks gradually decrease [32]. Therefore, the addition of guar gum shifts the failure mode from “structural collapse with large cracks” (“Y”-shaped) to a more controllable shear failure (“V”-shaped). This change is primarily due to the enhancement of the cohesive forces between soil particles by guar gum, thereby increasing the ability of the overall structure to resist the formation of large-scale cracks.

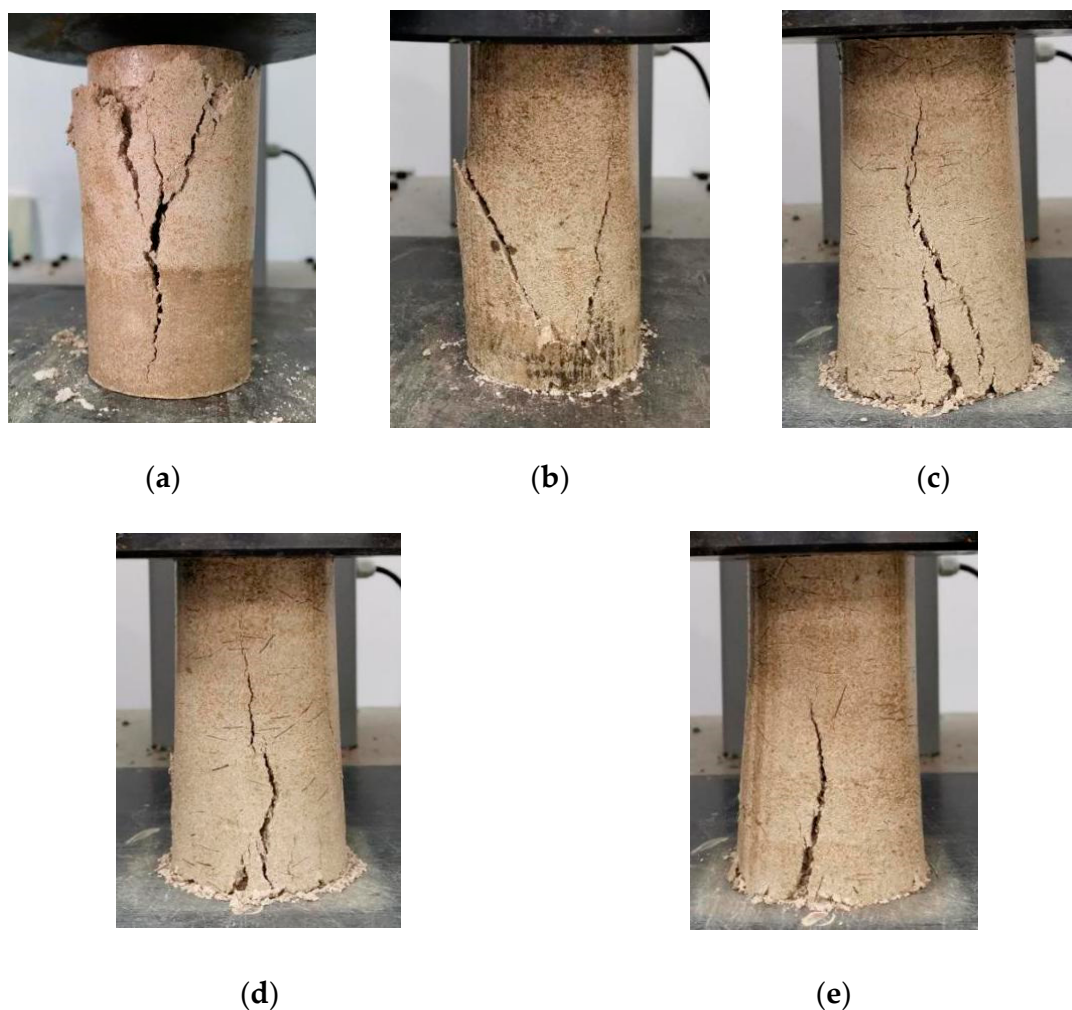


**Figure 10.** Failure mode of unconfined compressive strength sample: (a) G0P0L0; (b) G2P0L0; (c) G2P0.2L6; (d) G2P0.4L6; (e) G2P0.6L6.

From Figure 10c–e, it can be seen that the failure morphology of the guar gum–palm fiber composite-improved soil samples differs from that of the natural soil and the guar gum modified soil. After adding palm fibers, numerous fibers are distributed on the surface of the cylindrical sample. Under axial force, the cracks in the sample do not expand laterally to the sides as in the previous two samples, forming a “Y”-shaped crack or inclined shear failure surface. Instead, a vertical crack that expands upwards is formed. When the palm fiber length is 6 mm, as the palm fiber content increases from 0.2% to 0.6%, the length of the vertical crack gradually shortens, and the width of the crack’s lateral expansion gradually decreases. This indicates that the addition of coir fibers to guar gum-treated soil significantly affects the longitudinal crack propagation length and lateral crack propagation width of the samples. As the coir fiber content increases, the contact area between the soil and coir fibers expands, and the friction at the coir-expansive soil interface also increases. The fibers play a good bridging role between soil particles [19]. When cracks form and propagate under axial stress, the coir fibers enhance the material’s tensile strength and crack resistance through their interwoven distribution in the crack region, effectively suppressing the further propagation of cracks. The flexibility and elastic modulus of the coir fibers help to disperse stress concentration and reduce potential damage during the crack propagation process.

### 3.4. Triaxial Compression Strength Test

#### 3.4.1. Stress–Strain Relationship Curve of Improved Expansive Soil

Figure 11a–c analyzes the influence of guar gum and palm fiber content on the stress–strain evolution of improved expansive soil. Under the same confining pressure conditions, both the stress–strain curves of the untreated soil and the improved soil exhibit strain-hardening characteristics [28,33]. Specifically, the stress–strain relationship curves of the 2% guar gum-improved soil and the guar gum–palm fiber composite-improved soil are both higher than that of the untreated soil. As the confining pressure and palm fiber content increase, the curves progressively shift upward, and the difference in principal stress at the same strain continues to increase. When the confining pressure is 300 kPa, the peak principal stress difference of the G0P0L0 sample is 311.34 kPa, while the peak principal stress difference of the G2P0L0 sample is 386.85 kPa, which is an increase of 24.25% compared to the G0P0L0 sample. Among the composite-improved soils, the sample with the highest peak principal stress difference is G2P0.6L6, reaching 492.47 kPa, an increase of 27.30% compared to the G2P0L0 sample. In summary, with the increase in palm fiber content, the peak principal stress difference gradually increases, significantly enhancing the shear strength of the improved soil [34,35].

#### 3.4.2. Shear Failure Modes of Improved Expansive Soil Samples in Triaxial Compression Test

Figure 12 illustrates the shear failure modes of untreated expansive soil, guar gum-improved expansive soil, and composite-improved expansive soil samples during the triaxial compression test. As shown in the Figure, the G0P0L0 sample exhibits a shear brittle failure mode, while the G2P0L0 sample and the guar gum–palm fiber composite-improved soil sample demonstrate bulging failure. Under the same guar gum content conditions, the shear failure deformation of the G2P0L0 sample is significantly lower than that of the G0P0L0 sample. Moreover, as the palm fiber content increases, the deformation of the improved expansive soil gradually decreases, with the G2P0.6L6 sample exhibiting the least degree of bulging failure. Xu J et al. [36] also indicated that the incorporation of fibers can transform the failure mode of the sample from brittle failure to plastic failure.

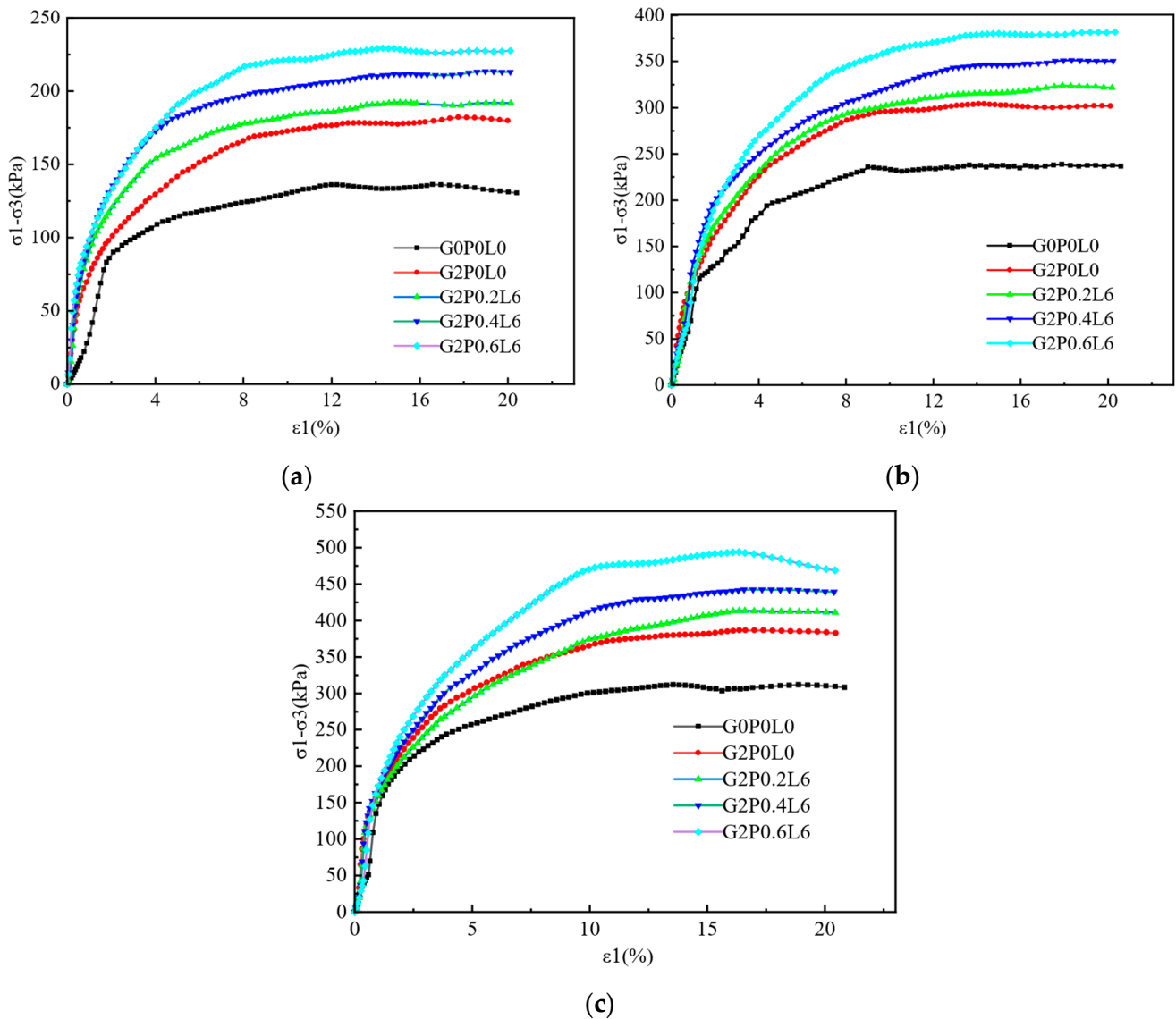


**Figure 11.** Influence of the dosages of guar gum and palm fiber on the stress–strain relationship of the improved expansive soil: (a) confining pressure of 100 kPa; (b) confining pressure of 200 kPa; (c) confining pressure of 300 kPa.

This indicates that the addition of guar gum fills the voids between soil particles with the gel-like substance produced by the hydration reaction, enhancing the bonding between particles and thereby increasing the soil's cohesion, thus altering the failure mode of the soil sample. The incorporation of palm fiber, on the other hand, plays a reinforcement role. The palm fibers are encapsulated within the soil particles and gel-like substances, further enhancing the bonding between particles and improving the overall integrity of the soil structure. A single palm fiber restricts the misalignment slip between soil particles, and there is an interaction force between palm fibers. When two palm fibers intertwine, the interaction force between them restricts their movement. If multiple palm fibers form a fiber network, they create a fiber–soil contact interface, thereby enhancing the overall structure of the soil [31]. Due to the good toughness of palm fibers, they are less prone to breakage under external forces and are difficult to pull out, effectively transferring external loads to the fiber network, making the soil subjected to more uniform stress and improving its stability. Furthermore, the friction between fibers and soil particles increases the internal friction angle of the improved soil, significantly enhancing its shear resistance [37].

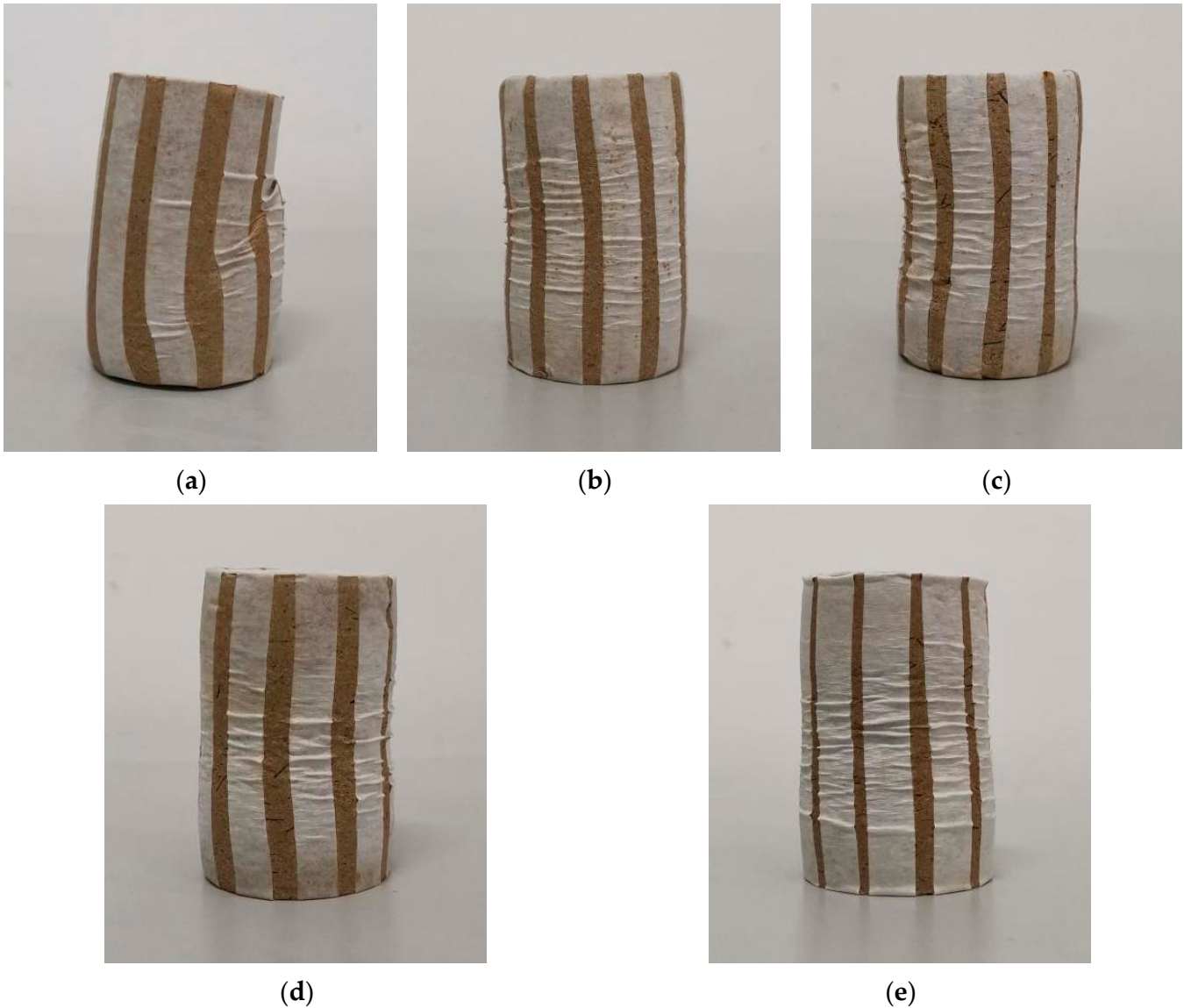


**Figure 12.** Shear failure morphologies of improved expansive soil specimens under different dosage conditions: (a) G0P0L0; (b) G2P0L0; (c) G2P0.2L6; (d) G2P0.4L6; (e) G2P0.6L6.

### 3.4.3. The Effect of Guar Gum and Palm Fiber Content on the Shear Strength Parameters of Modified Expansive Soil

The shear strength of soil is one of its important mechanical properties. In subgrade engineering, the stability of expansive soil slopes, foundation pits, and underground structures is controlled by the soil's shear strength. Therefore, the correct selection and application of soil shear strength parameters is of great significance in engineering practice. The shear strength of soil is typically described by the Mohr–Coulomb failure criterion:

$$\tau = c + \sigma \cdot \tan(\phi) \quad (4)$$

where  $\tau$  is the shear strength,  $c$  is the cohesion,  $\sigma$  is the normal stress acting on the failure plane, and  $\phi$  is the internal angle of friction. The internal angle of friction refers to the angle of the resistance generated when soil particles frictionally interact. It reflects the soil's ability to resist sliding under shear forces. By plotting the relationship curve between shear stress and normal stress under different confining pressures, a linear fitting curve can be obtained. The internal angle of friction is the slope of this line. This process is automatically

completed by the data acquisition and analysis software of the triaxial apparatus. The relationship curves between the content of raw soil, guar gum, and palm fiber and the shear strength parameters (cohesion and internal friction angle) of modified expansive soil are shown in Figure 13.

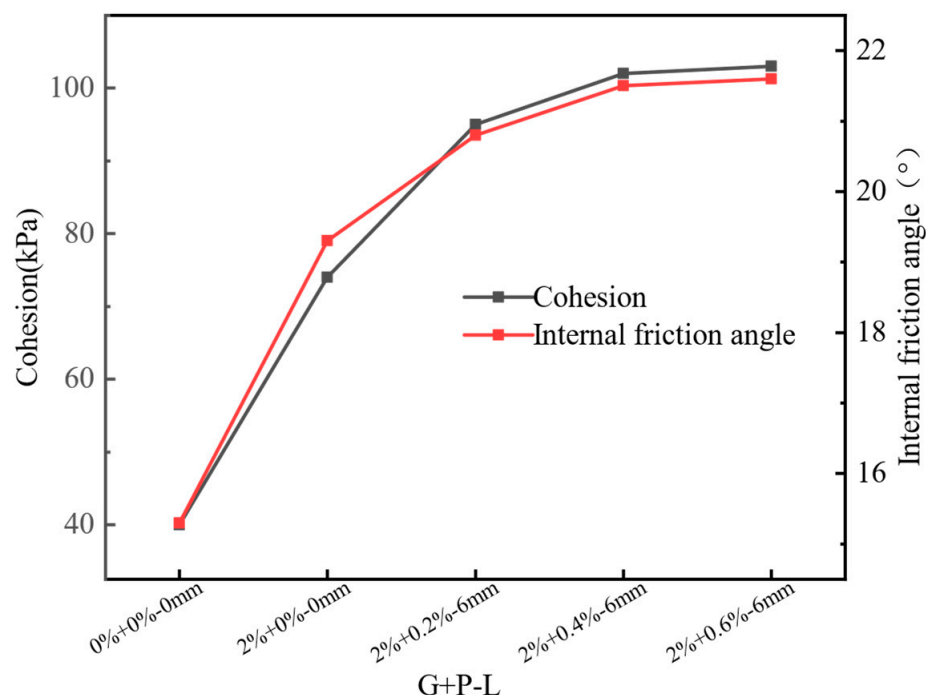


**Figure 13.** Relationship between the dosages of guar gum and palm fiber and the shear strength indexes of the improved expansive soil.

From the figure, it can be seen that the cohesion and internal friction angle of the G2P0L0 sample significantly increased compared to the natural expansive soil, with a rapid rate of increase. When the guar gum content is 2%, the shear strength parameters of the composite-modified expansive soil increase with the increase in palm fiber content, but the growth rate gradually slows down. When the palm fiber content reaches 2% + 0.6% – 6 mm, the increase in shear strength parameters tends to level off, indicating that the modification effect is approaching saturation. The cohesion and internal friction angle of the G2P0.6L6 sample reached 103.56 kPa and 21.68°, respectively, showing an improvement of 52.1% and 12.4% compared to the G2P0L0 sample. The experimental results show that the differences in the triaxial shear strength of the composite modified soil with different palm fiber contents are related to both cohesion and internal friction angle, with a larger influence from cohesion. This phenomenon is consistent with the study by Widiанти A et al. [19].

The reason for the change in the relationship curves of the shear strength parameters of the modified expansive soil is as follows: guar gum itself has a thickening effect. After being added to the soil, the gel-like products formed through hydration reactions can agglomerate the soil particles together, creating a cohesive structure [38]. At the same time, some of the gel-like products fill the voids between soil particles, significantly reducing the soil's porosity and increasing its compaction. Moreover, the addition of gel-like products reduces the thickness of the water film between particles, making the distance between particles smaller, thus enhancing the mechanical interlocking between particles. This is reflected in the rapid increase in the cohesion and internal friction angle of guar gum-modified soil [39].

When palm fibers are added to expansive soil, a fiber network is formed within the soil. The soil particles and the hydration products of guar gum surround the palm fibers, and through interface friction and stress transfer mechanisms, the displacement of

particles is restricted. The toughness of the palm fiber itself improves the soil's resistance to deformation. As the palm fiber content increases, the distance between adjacent palm fibers within the soil gradually decreases, forming a "fiber-rich zone." This leads to a reduction in the contact area between soil particles, weakening the interparticle bonding force, reducing the mechanical interlocking and frictional resistance, and thus affecting the shear strength of the soil. Previous studies have shown [29,35] that there is a critical value for the fiber content, and once this value is exceeded, the strength improvement of the soil gradually approaches saturation, which is consistent with the experimental results in this paper. Therefore, the growth of shear strength parameters gradually slows down. The relationship curve in the figure indicates that when the palm fiber content is 0.6%, the increase in shear strength parameters is small, suggesting that this content is close to the optimal amount of palm fiber. Combining the results of the disintegration test and the unconfined compressive strength test mentioned earlier, it can be concluded that the optimal mix for modifying expansive soil is 2% guar gum and 0.6% and 6 mm palm fiber.

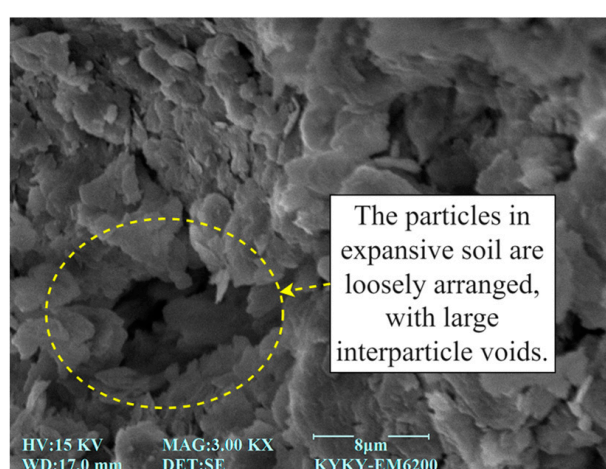
### 3.5. Mechanism Analysis of Guar Gum-Improved Soil

Figure 11 illustrates the microscopic structural characteristics of the gel formed after guar gum hydration, which wraps and cements the expansive soil. After guar gum is mixed with soil, the gel matrix generated by the hydration reaction forms a gel film (as shown in Figure 14a) through stretching. The gel film fills the pores of the soil, preventing the internal water film from further thickening and reducing the contact between water molecules and clay minerals such as montmorillonite. At the same time, part of the gel matrix, through hydrogen bonding, binds with the cations on the surface of soil particles, wrapping around the particles and subsequently cementing them together, forming a cemented material and filling the pores between soil particles (as shown in Figure 11b). This structural change reduces the inter-particle voids and increases the bonding strength, making the soil structure more compact and resistant to water lubrication. Acharya R et al. [32] also pointed out that guar gum, as a biopolymer, has effects such as filling, wrapping, and cementing the microstructure of the stabilized surface soil. The wrapping effect of guar gum on the soil particles prevents the particles wrapped by the hydrated guar gum products from coming into contact with external moisture, thereby inhibiting the lubricating effect of water molecules on the soil particles and effectively controlling the misalignment and sliding between particles. On a macroscopic scale, this results in improved cohesion and friction resistance of the soil [39]. Meanwhile, the cementing effect of guar gum between soil particles improves the bonding strength between the particles, allowing for better transmission of internal stress under external loads, leading to more uniform stress distribution on the particles [23,40], thereby enhancing the soil's resistance to disintegration and compressive strength.

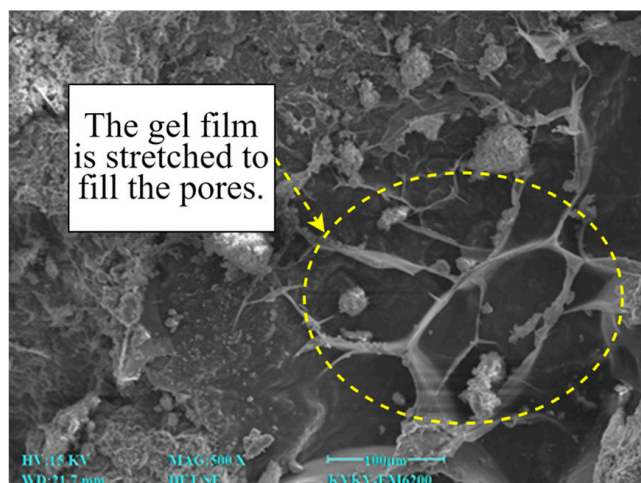
### 3.6. Mechanism of Guar Gum–Palm Fiber Composite Improvement of Expansive Soil

Figure 15 illustrates the microstructure characteristics of guar gum–palm fiber composite-modified expansive soil. As shown in the figure, when the guar gum content is 2%, the palm fiber content is 0.4%, and the fiber length is 6 mm, the fiber reinforcement causes the fibers within the soil to interlace, forming a stable three-dimensional reinforcing structure [41]. After the hydration reaction of guar gum, its high viscosity strengthens the fiber-soil interface, making it difficult for the palm fibers to be pulled out, thereby effectively inhibiting the misalignment slip between soil particles. When the soil is under compression, the palm fibers share part of the load through the "bridging effect" [42] (as shown in Figure 15a), thereby delaying the destruction and deformation of the soil structure. When the soil structure is severely damaged, cracks may develop between the soil particles, and

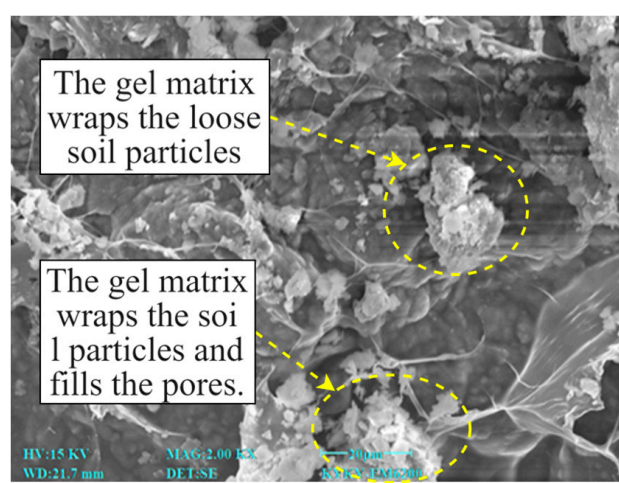
the fibers will connect the soil mass on both sides of the crack [33] (as shown in Figure 15b). At this point, the frictional resistance between the fibers and the soil particles helps to suppress the crack's expansion and maintain the structural integrity of the soil sample after failure. On a macroscopic level, this results in a significant improvement in the soil's compressive strength and deformation resistance. This reinforcement mechanism aligns with findings in advanced composite materials, where fiber distribution and interfacial bonding critically govern mechanical performance [43]. However, if the length or content of the palm fibers is excessive, it may lead to the aggregation of fibers within the soil (as shown in Figure 15c), increasing the contact area between the fibers [31]. In this case, the mechanical interlocking force and frictional resistance between the soil particles will decrease, resulting in a reduction in the soil's strength and structural stability. Therefore, to maximize the reinforcing effect of the fibers, the length and content of the fibers should be strictly controlled.



(a)



(b)



(c)

**Figure 14.** Micro-mechanism of the soil improved by guar gum: (a) the voids in expansive soil; (b) the stretching effect of the gel film; (c) the wrapping and filling effect of guar gum.

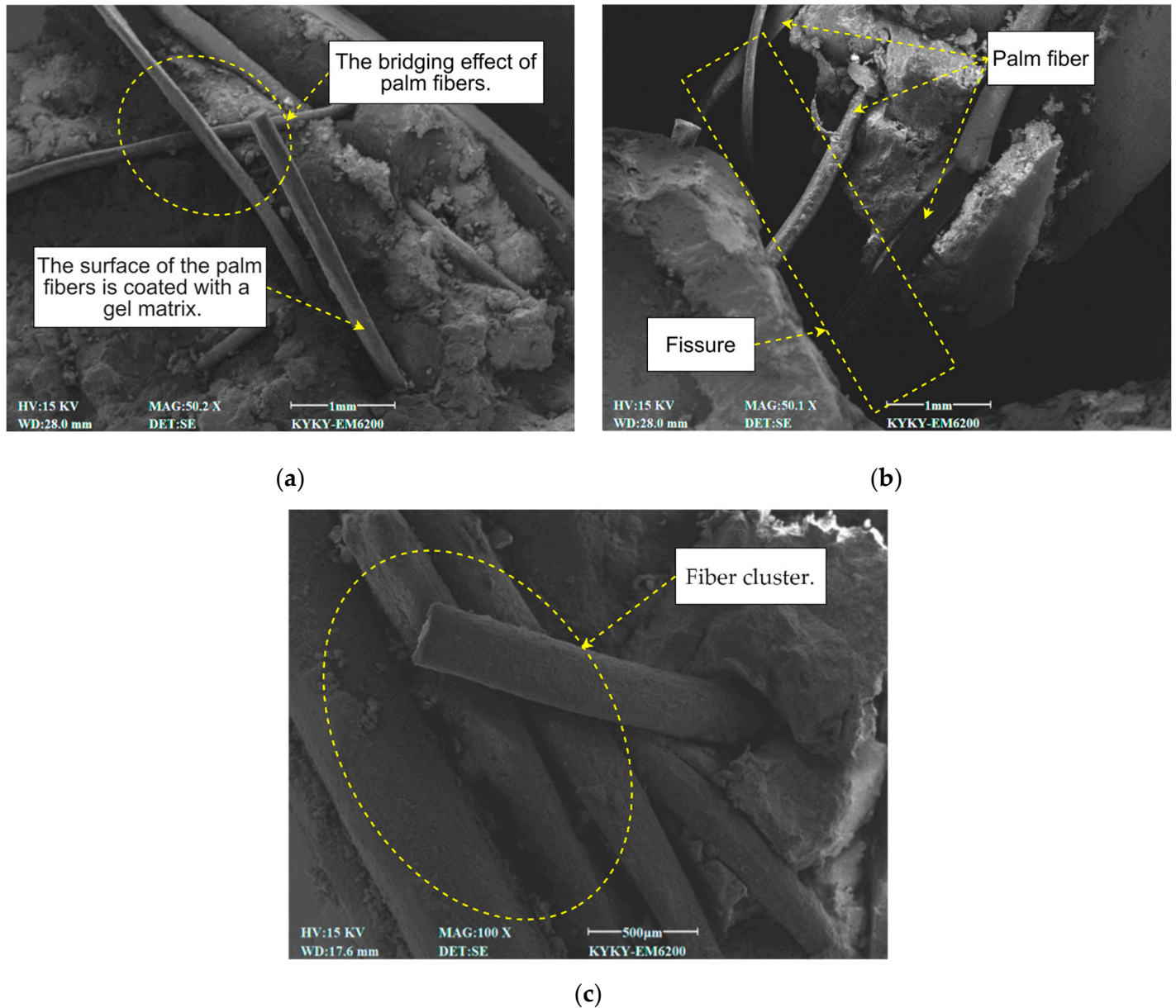


**Figure 15.** The microscopic mechanism of the soil improved by the composite of guar gum and palm fibers: (a) the bridging effect of palm fibers; (b) the inhibition of crack development by palm fibers; (c) the palm fibers accumulate and aggregate into clusters.

#### 4. Discussion

The study has demonstrated that guar gum and palm fiber are both effective in improving the properties of expansive soil. The results indicate that the combination of these materials significantly enhances the water stability, compressive strength, shear strength, and failure modes of the soil. Furthermore, the micro-improvement mechanisms highlighted by scanning electron microscope analysis provide valuable insights into how guar gum and palm fiber work synergistically to reinforce soil properties.

Based on the findings, the following conclusions can be drawn:

1. Guar gum can effectively improve the water stability of expansive soil. With the increase in guar gum content, the disintegration resistance of the samples significantly improves. When the guar gum content reaches 2%, the disintegration rate of the sample reaches the threshold of 0.85% and virtually no further disintegra-

tion occurs. Therefore, it is recommended that the guar gum content in practical applications be 2%.

2. Both guar gum and guar gum–palm fiber composite materials can enhance the unconfined compressive strength of expansive soil, with the guar gum–palm fiber composite material showing the best improvement. Under the condition of a fixed palm fiber content, the compressive strength of the soil initially increases and then decreases as the palm fiber length increases. When the palm fiber content is 0.6% and the length is 6 mm, the unconfined compressive strength of the composite-improved soil increases the most, with a 20.9% higher compressive strength compared to expansive soil improved with 2% guar gum.
3. The addition of palm fiber can improve the shear strength of guar gum-treated soil. As the palm fiber content increases, the stress–strain curve of the composite-improved soil gradually rises. The two shear strength indicators, cohesion and internal friction angle, both increase as the palm fiber content rises. When the ratio is 2% guar gum and 0.6%–6 mm palm fiber, the increase in the two shear strength indicators levels off, with increases of 52.1% and 12.4%, respectively, compared to pure guar gum-treated soil. However, further increasing the palm fiber content is detrimental to the improvement of the soil's shear strength.
4. Guar gum and palm fiber have a significant impact on the failure modes of the expansive soil samples. Under axial pressure, the guar gum-improved soil exhibits a “V”-shaped failure, with cracks not penetrating the sample, while the composite-improved soil shows irregular vertical cracks, and as the content increases, the cracks gradually shorten. Under shear failure, both guar gum-improved soil and guar gum–palm fiber composite-improved soil show bulging failure, and the deformation gradually decreases with the increase in palm fiber content.
5. Scanning electron microscope analysis of the micro-improvement mechanism of guar gum–palm fiber-improved soil reveals that the gel matrix generated by the hydration reaction of guar gum can enhance the bonding strength of soil particles through stretching, wrapping, and filling, thus improving the water stability and mechanical properties of expansive soil. The reinforcement effect of palm fiber further enhances the mechanical properties of the improved soil.
6. This composite improvement method can not only effectively increase the bearing capacity and deformation ability of expansive soil but also is environmentally friendly and has broad potential for promotion. However, this study is limited to expansive soil in Nanning, Guangxi, China, and the results are applicable only under conventional conditions. Therefore, the identified optimal ratio has certain limitations, and further research and verification are needed for specific situations.

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