Research Article

Macroscopic Mechanical Properties and Microscopic Bonding Mechanisms of Glass Fiber-Modified Loess

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Focusing on the performance improvement of glass fiber-modified loess, a series of laboratory tests were carried out, and the macroscopic mechanical properties of glass fiber-modified loess were studied by conventional triaxial shear tests. With the help of scanning electron microscopy (SEM), the pores and cracks image analysis system (PCAS) and nuclear magnetic resonance (NMR) tests, the microscopic properties of the improved loess were studied qualitatively and quantitatively from three aspects: mode of structural contact, pore morphological characteristics and pore structure arrangement characteristics. Finally, the interface zone bond-slip model was used to analyze the internal mechanism of glass fiber and loess interface zone slip. The macroscopic test results show with the same glass fiber length, the shear strength, cohesion and internal friction angle of the modified loess all increased first and then decreased with increasing incorporation of glass fibers. And the optimal ratio of glass fibers is 0.6%. Under the same fiber ratio, the shear strength and cohesion of the improved loess continued to increase with increasing fiber length. The optimal fiber length used in the project was 9 mm. Qualitative analysis of the SEM images show that with the increase in the glass fiber incorporation ratio, the fiber increasingly sutures the cracks in the soil and tightens the soil at both ends of the cracks. Quantitative analysis shows that the proportion of pore area is the largest at the 0.8% mixing ratio, followed by the 0% mixing ratio, and the smallest at the 0.6% mixing ratio. It can be seen from the NMR test results that the $T_2$ spectral distribution curve under the fiber ratios of 0.2%–0.6% is shifted to the left compared with the ratios of 0% and 0.8%. The peak-top signal intensity of the main spectrum peak when the fiber ratio is 0.6% is the weakest.

1. Introduction

Loess is the most widely distributed soil layer in Northwest China. Due to its special soil properties, loess natural disasters are more likely to occur in environments with abundant rainfall, sufficient sunshine, and rapid changes in groundwater level. Therefore, when loess is used in construction or engineering projects, it must be treated. There are various methods for improving loess, and most of them involve improvement or modification by adding other substances, but there are few reports on adding glass fiber to improve loess. Data show that China’s glass fiber material production ranks first in the world’s glass fiber production, and there are many categories that are used for a variety of applications [1]. Its excellent properties, high yield, and economic advantages grant it the potential to improve loess. In the construction of foundations in loess, the settlement and deformation of the foundation often occur due to the collapsibility of loess. Fiber-reinforced materials are commonly used to improve the mechanical properties of loess to prevent settlement and deformation of foundations. The research has the potential to advance construction methods.

Relevant research on improved loess mainly includes the following: Wang et al. [2] used cement and lime to improve the subgrade filling range under the action of freeze–thaw cycles and obtained certain experimental results. Zhang et al. [3] used loess and cement as modifiers to improve the compressive modulus of soft rock. Cui et al. [4] evaluated the deterioration mechanism of cement-improved soil under the action of dry-wet cycles by the CBR influence factor. Zhu et al. [5] studied the optimal ratio of road fly ash to improve soil. Dong et al. [6] used lignin to improve the thermodynamic properties of loess. Zhang et al. [7] used a new curing agent to study the erosion resistance of the improved loess.
Kong et al. [8] improved the collapsibility of loess by microbial induction. Jiang et al. [9] studied the fatigue characteristics of cement-modified soil. Zuo et al. [10] used xanthan gum and fiber to improve the compressive strength of loess. Tian et al. [11] mixed waste sand into the solidified loess with anti-solution force, which improved the intergranular cohesion of the loess. This shows that there have been many improvements for various properties of loess, and improvement has become an important method for improving soil properties and reducing engineering costs in basic engineering.

Relevant research on fiber materials as basic substances for engineering improvement mainly includes the following: Yang et al. [12] mixed bamboo fiber material into concrete and proved that it can improve the tensile and flexural strength of concrete through mechanical tests. Zhang et al. [13] analyzed the internal mechanism and mechanical properties of plant fiber composites and predicted the law of performance attenuation. Chen et al. [14] incorporated steel fibers into concrete and proposed the optimal incorporation volume fraction of steel fibers based on seismic loads. Liu et al. [15] mixed fibers into cement-soil to study its durability and mechanical properties, and Ran et al. [16] mixed straw fibers into silt to repair cracks. It can be seen from this that fiber materials have been widely used in the improvement of various materials and have achieved good results. As a type of fiber material, glass fiber has better properties in engineering and its use is likely to develop into a trend for improving materials [17]. However, there are few studies on glass fibers, and further research is needed on its mechanism.

Relevant research on the microscopic properties of soil mainly includes the following: Bai et al. [18] studied the microscopic structure of paleosol by scanning electron microscopy (SEM) combined with nuclear magnetic resonance (NMR). Lv et al. [19] studied the microscopic properties of fiber-modified red clay by NMR. Feng et al. [20] obtained the calculation formula of three-dimensional porosity by SEM. Liu et al. [21] studied the microscopic properties of loess in frozen regions by NMR combined with SEM. Wang et al. [22] studied the microscopic mechanism of saline soil by SEM combined with NMR. At present, microscopic research on soil is focused on NMR and SEM. Research on the microscopic characteristics of improved soil can also be comprehensively studied by SEM combined with NMR. The above two microscopic research methods can qualitatively analyze images or quantitatively analyze the pores in the soil. To comprehensively study the microscopic mechanism of the improved soil, the pores and cracks image analysis system (PCAS) can be used to quantitatively study particle or pore abundance and cracks and their arrangement. SEM and NMR can be combined with PCAS software. The microscopic properties of the improved soil can be analyzed more comprehensively. In one relevant study on using the PCAS method, Liu et al. [23, 24] used it to conduct quantitative analysis of cracks in dry samples, and based on this, they used clay samples for popularization and application, analyzed and solved various parameters of clay samples, and obtained good quantitative results.

Based on the above research and considering the wide distribution of loess and the settlement and deformation of foundations caused by the collapsibility of loess in water, in this paper, a compaction test of glass fiber-modified loess is conducted to study the compaction characteristics and optimal moisture content of glass fiber-modified loess. Then, the triaxial consolidation drainage shear test was carried out to analyze the improvement effect of glass fiber material on the macroscopic mechanical properties of loess. Subsequently, SEM and NMR experiments were carried out to study the microscopic properties before and after incorporation of glass fiber. Finally, the bonding mechanism between the glass fiber and loess was studied by using the interface slip model.

### 2. Test Overview

#### 2.1. Experimental Material

The test loess sample was taken from a construction site of a foundation project in Xi’an. It was a Quaternary sediment. The soil sample was yellow-brown with large pores, no obvious calcareous nodules were found, and the soil quality was relatively uniform. The basic physical and mechanical indicators are shown in Table 1. Among them, the liquid-plastic limit index is measured by the “Geotechnical Test Regulations” (GB/T 50123–2019), and the content of sand, silt, and clay is measured by a laser particle size analyzer and sieving. The dry density is measured according to the compaction test regulations in the specification, and the particle size distribution is measured by a Bettersize2600 laser particle size distribution analyzer (wet method). The particle size distribution curve is shown in Figure 1.

Glass fibers with good performance are the more common E-alkali-free glass fibers. The glass fiber is made by drawing after the glass is melted at high temperature (the pool kiln drawing method) [1]. The diameter is 3–24 μm, and the initial length is 50–60 cm. To meet the blending conditions, it is cut into 3, 6, 9, and 12 mm lengths to be blended and used for preparing samples. The glass fiber material to be used is shown in Figure 2, and its main material components and basic properties and compositions are shown in Table 2.

#### 2.2. Test Plan

##### 2.2.1. Sample Preparation Plan

After determining the research objectives, 5 groups of samples (S1, S2, S3, S4, and S5) were prepared, of which 4 groups (S1, S2, S3, S4) were modified loess samples with different glass fiber contents and

| Natural density (g/cm³) | Natural water content (%) | Optimal moisture content (%) | Maximum dry density (%) | Liquid limit (%) | Plastic limit (%) | Cohesion (kPa) | Internal friction angle (°) |
|-------------------------|---------------------------|----------------------------|-------------------------|-----------------|-----------------|---------------|--------------------------|
|                         |                           |                            |                         |                 |                 |               |                          |
| 1.65                    | 13.2                      | 16.8                       | 1.79                    | 32              | 21              | 26.8          | 17.3                     |

**Table 1: Basic physical and mechanical indicators.**
**Figure 1:** Particle gradation diagram.

**Figure 2:** Glass fiber material to be used.

**Table 2:** Composition and basic properties of E-glass fiber.

| Type       | SiO₂ (%) | Al₂O₃ (%) | CaO (%) | MgO (%) | Na₂O (%) | K₂O (%) | B₂O₃ (%) | Relative density | Monofilament strength (GPa) | Tensile modulus of elasticity (GPa) | Softening point (°C) |
|------------|----------|-----------|---------|---------|----------|---------|----------|-----------------|-----------------------------|-----------------------------------|---------------------|
| E-glass fiber | 52.4     | 14.4      | 17.2    | 4.6     | 0.8      | 10.6    | 2.56     | 3.6             | 76                          | 850                               |                     |
lengths, and 1 group (S5) was the plain soil sample used for the control. According to the research objectives, the glass fiber content of groups S1, S2, S3, and S4 was 0.2%, 0.4%, 0.6%, and 0.8%, respectively, and the glass fiber lengths are 3, 6, 9, and 12 mm (each sample contained fibers of all lengths). To fully focus on the exploration of glass fiber-modified loess properties, the optimal moisture content and maximum dry density were selected for sample preparation. The test scheme is shown in Table 3.

### 2.2.2. Conventional Triaxial Shear Test Protocol
Referring to the “Geotechnical Test Regulations” (GB/T 50123–2019) triaxial compression test regulations, the optimal moisture content and the maximum dry density determined by the compaction test were used to prepare triaxial shear specimens with a specification of φ39.1 × 80 mm using a shear rate of 0.8 mm/min. To obtain a more reliable variation of cohesion and internal friction angle, the confining pressure is 50 kPa, 100 kPa, 150 kPa, and 200 kPa.

The triaxial shear test needs to clarify the following: (1) The compressive strength under different confining pressures, different fiber incorporation ratios and different glass fiber lengths and the shear strength obtained by Mohr Coulomb theory, (2) Stress–strain characteristics, failure strength, elastic modulus, cohesion and internal friction angle, and other related parameters under different working conditions.

### 2.2.3. Micro Test Plan
To more reasonably explain the microscopic mechanism of the improvement of loess after adding glass fiber, the samples of plain soil after curing and different proportions (0.2%, 0.4%, 0.6%, and 0.8%) and different lengths (3 mm, 6 mm, 9 mm, and 12 mm) were selected. Samples were first subjected to SEM. When designing the SEM test, to ensure that the results are more representative, it is necessary to scan the same sample at multiple points, select similar pictures to analyze the qualitative results, and then use PCAS software. The system obtains microscopic parameters for quantitative analysis of the improved soil samples. Finally, because SEM can only take part of the representative soil samples for testing and the whole soil sample cannot be observed, to analyze the microscopic characteristics of the soil sample as a whole, an NMR test is designed for further analysis.

### 2.3. Test Principle Analysis

#### 2.3.1. SEM Test Qualitative Analysis Principle
Compared with ordinary microscopy, SEM has the advantages of a wide magnification range, large depth of field and imaging visualization. Its working principle is to “bombard” the surface of the sample by emitting high-energy electron beams. Under the action of the offset coil, the incident direction is changed, the microscopic morphology of the sample is restored by the reflected secondary electrons, and the composition of the sample is qualitatively reflected by the backscattered electrons [25]. The working principle is shown in Figure 3 below.

#### 2.3.2. Principle of Quantitative Analysis with the PCAS
PCAS is a professional software used to analyze the characteristics of mineral composition, pores, soil particles and rock and soil fractures. The principle of identifying rock and soil fractures, pores, and rock and soil particle parameters is to use cluster analysis or grayscale. The image is divided into regions, the nodes around the target object are identified.
The principle is as follows: the relaxation mechanism is shown in Figure 4. Its calculation maximum to settle to zero [26]. A simplified diagram of the relaxation refers to the time it takes for the excited state hydrogen nuclear spin to the equilibrium state. Transverse this paper refers to the hydrogen nucleus. Relaxation refers received. The process is called NMR. The atomic nucleus in electromagnetic waves and forming a radio signal that can be received. The high-energy level, releasing energy in the form of electrical energy is formed by the nuclear spin absorbs energy and transitions to an excited state balanced state.

\[ T_2 = T_{2S} + T_{2D} \]

Figure 4: Schematic diagram of relaxation mechanism.

According to the pixel points, the positions of the cracks, pores, and soil particles are located through the nodes, and the binarized and vectorized images are used to extract the area, length, width, and angle of the cracks, pores, and particles. Probability entropy, fractal dimension, and other important parameters are also considered.

2.3.3. NMR Test Principle. The nuclear magnetic moment formed by the nuclear spin absorbs energy and transitions to a high-energy level, releasing energy in the form of electromagnetic waves and forming a radio signal that can be received. The process is called NMR. The atomic nucleus in this paper refers to the hydrogen nucleus. Relaxation refers to the process of stabilizing from the excited state of the hydrogen nuclear spin to the equilibrium state. Transverse relaxation refers to the time it takes for the excited state to maximum to settle to zero [26]. A simplified diagram of the relaxation mechanism is shown in Figure 4. Its calculation principle is as follows:

\[ \frac{1}{T_2} = \frac{1}{T_{2S}} + \frac{1}{T_{2D}} \]

where \( T_{2S} \) is the lateral surface relaxation and \( T_{2D} \) is the lateral diffusion relaxation.

2.4. Experimental Procedure. The experimental process and some test results are shown in Figure 5 below:

3. Analysis of Test Results

3.1. Mechanical Properties Analysis

3.1.1. Stress-Strain Curve Analysis

(1) Stress–Strain Curve Analysis for Different Fiber Ratios. When studying the effect of different glass fiber contents on the soil strength, the confining pressure and the fiber length are kept constant. A confining pressure of 150 kPa with a better curve effect is taken, and the stress–strain curves of different compositions are shown in Figure 6.

It can be seen from Figure 6 that under a confining pressure of 150 kPa and a fiber length of 12 mm, with the increase in the glass fiber mixing ratio, the stress–strain curves of the improved loess show increased hardness compared to that of the control soil. When the mixing ratio is 0.2%, the principal stress of the improved loess is higher than that of the plain soil, with an increase of approximately 48%. With the addition of 0.4%, the principal stress of the improved loess is significantly increased (approximately 69.7% higher). When the mixing ratio is 0.6%, the principal stress of the improved loess is approximately 94.8% higher than that of the plain soil. At this ratio, the difference between the principal stress of the improved loess and the plain soil is the largest, so 0.6% is determined to be the optimal mixing ratio. When the mixing ratio is 0.8%, there is a less considerable increase in principal stress of the improved loess compared with the control. The principal stress is significantly lower than the improvement state of the 0.4% mixing ratio but still higher than that of the 0.2% mixing ratio.

(2) Analysis of Stress–Strain Curves for Different Fiber Lengths. When studying the effect of different fiber lengths on the strength, the confining pressure and mixing ratio are kept constant. The confining pressure of 150 kPa with better curve effect and a mixing ratio of 0.6% are used, and the stress–strain curves of different lengths are studied, as shown in Figure 7.

It can be seen from Figure 7 that under a confining pressure of 150 kPa and a mixing ratio of 0.6%, with increasing fiber length, the stress–strain curve of the improved loess is in a state of continuous growth, and the mixing ratio is within the range of 3 mm–9 mm. Thus, the principal stress enhancement effect is better. With a fiber length of 12 mm, the improvement of the principal stress of the improved loess is the largest, but compared with other fiber lengths, the enhancement of the principal stress is smaller. In view of the improvement effect, it is considered that 12 mm is the optimal fiber length. However, for practical engineering, the 12 mm length is less economical than the 9 mm length, and its improvement effect is only slightly better than that of the improved loess with a 9 mm mixing length.

3.1.2. Damage Strength Analysis. Figure 8 shows that with the increase in the glass fiber ratio from 0% to 0.6%, the failure strength of the improved loess shows an upward trend, and with the increase in the confining pressure, the failure strength also increases. This is because when the confining pressure increases, the pores of the soil sample are compacted, resulting in a larger contact surface between the glass fibers and the soil particles, which enhances the friction and cohesion between the glass fibers and the soil particles. Similar to the ratio of fibers, there was also a continuous upward trend in shear strength with increasing fiber length, although there was a smaller rate of increase with a length of 12 mm. As the ratio of fibers increased from 0.6% to 0.8%, the failure strength of the improved loess showed a downward trend. In general, after adding glass fiber, the
failure strength of the modified loess has different degrees of enhancement. It can be seen from the broken line segments of each peak point that the failure strength of the 0.6% ratio is the largest, and the ratio of 0.8% is close to the failure strength of the 0.2% ratio, but it is still higher than the failure strength of the plain soil. There are cases where glass fibers are entangled into a group, but some glass fibers play a reinforcing effect.

3.1.3. Analysis of Cohesion and Angle of Internal Friction. Figure 9 shows that the cohesion of the improved loess shows a trend of first increasing and then decreasing with
increasing ratio of fiber. When the ratio is 0.6%, the cohesion reaches the peak value, and the cohesion keeps increasing with increasing fiber length. Figure 9(a) shows that the cohesion value of the 12 mm fiber length is slightly higher than that of the 9 mm length. This phenomenon is consistent with the trend in the failure strength. In Figure 9(c), the cohesion with fiber lengths in the range of 9 mm–12 mm is almost the same, indicating that 12 mm is already the limit of the fiber length, and continuing to increase it will lead to a decrease in cohesion. From Figures 9(b) and 9(d), it can be seen that the fiber ratio and length have little effect on the internal friction angle of loess, ranging from 0.6 degree to 4.5 degree.

3.1.4. Optimal Fiber Amount and Length. Based on the above mechanical analysis results, it is believed that the optimal mixing ratio of glass fiber to improve the mechanical properties of loess is 0.6%, and the optimal length is 12 mm. The mechanical properties of 12 mm are smaller than those of other mixing lengths. However, for practical applications, although the improvement is the best, but the economics of 12 mm fibers are poor. Therefore, the optimal fiber length in this project is 9 mm.

3.2. Micro Mechanism Analysis. Due to the particularity of loess itself, its particle composition, pore size, arrangement, and structural contact forms are complex and diverse. After adding glass fibers, their mechanical properties are more complex, so it is difficult to comprehensively analyze their microscopic features by simple qualitative analysis methods. Therefore, in this study, SEM, PCAS, and NMR were used to analyze the microscopic mechanism through qualitative and quantitative, partial, and comprehensive methods.

3.2.1. Qualitative Analysis of SEM Results. The SEM test soil sample was analyzed by the triaxial shear test. Since the
scanning electron microscope is a high-precision instrument, when taking the soil sample after the triaxial shear test, the glass fibers with the most uniform distribution and the most representative should be taken. Analysis method of SEM test results refer to [27–30].

To compare the microstructure of soil samples with different mixing ratios and plain soil samples, it is necessary to keep the mixing length constant. In this study, the optimal length of 12 mm obtained from the above mechanical test was used as the control length. The samples were imaged by SEM at 500, 1000, 2000, and 5000 times magnification. Due to space reasons, the magnifications which can best show the differences before and after mixing were selected for analysis (500, 2000, and 5000 times magnification). The scanning results of glass fibers and the scanning results of 12mm glass fibers with 0.4%, 0.6%, and 0.8% incorporation ratios were qualitatively analyzed. The SEM results are shown in Figure 10.

It can be seen from Figure 10 that with the increase in the glass fiber incorporation ratio, the degree and manner of the glass fibers penetrating the cracks in the soil are different. When the mixing ratio is 0% (plain soil), the cracks develop freely. When the mixing ratio is 0.2%, the glass fiber can connect the upper and lower soils, but the inhibition of soil cracks is not obvious. When the mixing ratio is 0.4%, the
Glass fiber can pass through the crack and can play the role of connecting the two sides of the crack, and the shear strength of the improved loess is significantly improved in mechanical testing. When the mixing ratio is increased to 0.6%, the glass fibers locally form a quadrilateral structure, intertwining with each other, and there is no overhead phenomenon, which can penetrate most of the cracks. At this ratio, the inhibition of cracks is the most obvious, and the corresponding shear strength is also the highest. When the mixing ratio is 0.8%, it can be seen that the glass fibers are intertwined and staggered to form an overhead structure, but some fibers still penetrate through the cracks, so the shear strength is still higher than that of plain soil, but the overhead structure also makes the internal pores of the modified loess larger, thereby losing some of its strength.

Figure 11 shows that with the change in the glass fiber incorporation ratio, the contact mode between the soil structure and the glass fiber interface and the pore size exhibit great changes. At a ratio of 0% (plain soil), the point-to-point contact mode of soil particles is more prevalent, followed by point-edge contact and with less face-to-face contact. At a 0.2% incorporation ratio, the soil-glass fiber interface is dominated by contact between flaky particles and round particles, and there are several large pores around the soil-glass fiber interface. At a 0.4% ratio, the glass fibers are confined to each other and connected closely, the interfacial contact is dominated by lamellar soil, and the interfacial pore space is not much different from that at the 0.2% admixture ratio. At a 0.6% incorporation ratio, it can be seen from the figure that the soil is relatively dense, and the glass fiber-soil interface is almost a whole sheet contact with fewer pores around the interface. At a ratio of 0.8%, glass fibers intertwine with each other, breaking away from the soil, a large number of hollow pores are observed, and glass fibers cannot play a reinforcing role and wind into a group, resulting in more and larger pores.

3.2.2. Quantitative Analysis of SEM Results. The images at 500 times magnification used in the qualitative analysis were selected for quantitative analysis of pore-related parameters, and PCAS was used to carry out binarization and vectorization processing. Due to space reasons, only the binarization and vectorization processing of the modified loess under the glass fiber mixing ratios of 0%, 0.6%, and 0.8% are shown in Figure 12.
Figure 11: Qualitative analysis with glass fiber incorporation (2000 times magnification) (a) 0% plain soil (b) 0.2% incorporation soil (c) 0.4% incorporation ratio (d) 0.6% incorporation ratio (e) 0.8% incorporation ratio.

Figure 12: Binarized and vectorized images of improved loess with different ratios of glass fiber (a) 0% plain soil (b) 0.6% incorporation ratio (c) 0.8% incorporation ratio.
Percentage of Pore Area

The proportion of pores in the soil will directly affect the strength of the soil. Too many pores will lead to insufficient cohesion between soil particles, resulting in a decrease in the strength of the soil. Therefore, it is very important to study the proportion of pores before and after glass fiber is added. The pore area ratio can be calculated by the following formula (2):

\[ \eta = \frac{S_1}{S} . \]

(2) Pore Abundance

Pore abundance [31] refers to the fullness of pores in soil. Usually, a certain surface of pores is approximated as an ellipse, and the degree of closeness to a circle is reflected by the corresponding relationship between the short axis and the long axis. The calculation of pore abundance is done by the following formula (3):

\[ C = \frac{B}{L} . \]

The abundance was calculated according to the results of the average length and width of the major and minor axes obtained by the PCAS. When the mixing ratio is 0%, the average width of the soil pores is 13.66, the average length is 27.92, and the calculated average abundance obtained from formula (3) is 0.4893. When the mixing ratio is 0.2%, the average width of the soil pores is 15.54, the average length is 27.58, and the average abundance is 0.5636. When the mixing ratio is 0.4%, the average width of the soil pores is 12.44, the average length is 21.36, and the average abundance is 0.5824. When the mixing ratio is 0.6%, the average width of the soil pores is 14.34, the average length is 23.72, and the average abundance is 0.6046. When the mixing ratio is 0.8%, the average width of the soil pores is 11.65, the average length is 18.2, and the average abundance is 0.6401. This result was plotted in Figure 14.

It can be seen from Figure 14 that the abundance of pores increases continuously with the increase in the glass fiber content, which means that with the increase in the ratio, there is a great effect in changing the pores from flat to oblate.

(3) Pore Fractal Dimension

The pore fractal dimension [32] represents the complexity of pores in soil, which is essentially determined by the relationship between the area of pores in soil and the equivalent perimeter. It is calculated by the following formula (4):

\[ \log L = \frac{D}{2} \log A + C. \]

The fractal dimension values of pores under each incorporation ratio (0%, 0.2%, 0.4%, 0.6%, and 0.8%) are 1.2114, 1.2206, 1.2325, 1.2424, and 1.2528, respectively. It can be seen that with the increase in the glass fiber incorporation ratio, the fractal dimension of pores continuously increases, but the values are all in the range of 1.2–1.3. The data are plotted in Figure 15.

From Figure 15, it can be seen that the fractal dimension of pores increases with the incorporation ratio, indicating that the larger the glass fiber ratio, the more complex the pore structure.
Pore Orientation Probability Entropy

Soil pore orientation probability entropy [33, 34] is a parameter for the degree of orientation and arrangement of pores in soil. It is calculated probabilistically as the proportion of pores with the same orientation, so its range is [0,1]. An orientation probability entropy closer to 1 indicates that the arrangement of pores in the soil is more disordered. It is calculated according to formula (5):

$$H_m = - \sum_{i=1}^{n} F_i(\alpha) \log_m F_i(\alpha).$$

According to the data analyzed by the PCAS, when the incorporation ratio was 0%, the orientation probability entropy of glass fiber-modified loess was 0.9934, which is close to 1, indicating that the pore arrangement itself in the loess without incorporation was very chaotic. When the incorporation ratio increased to 0.2%, the orientation probability entropy of the improved loess was 0.986, which was slightly lower than that of the soil without glass fibers, indicating that the addition of glass fibers leads the pores in the soil to be more aligned. However, overall, it is still relatively disordered. When the incorporation ratio is increased to 0.4%, the orientation probability entropy is 0.986, which is slightly lower than that at a ratio of 0.2%. The orientation probability entropy at ratios of 0.6% and 0.8% were 0.9831 and 0.9771, respectively, which were smaller than those at other incorporation ratios. These results are plotted in Figure 16.

As seen from Figure 16, the orientation probability entropy of pores shows a continuous downward trend, indicating that the addition of glass fibers makes the friction and cohesion of the interface between glass fibers and soil particles change the arrangement of particles in the soil, thereby affecting the pore size. The arrangement mode makes the arrangement of pores develop in an orderly manner.

Analysis of NMR Results

Since SEM only allows for qualitative and quantitative analysis on a specific surface, the results are somewhat incomplete. Therefore, it is necessary to comprehensively analyze the overall pores of the improved loess in combination with the NMR test to reasonably verify the above results. Figure 17 shows the $T_2$ spectral distribution diagram at different glass fiber ratios. From the NMR data and Figure 17, it can be concluded that when the incorporation ratio is 0%, the $T_2$ spectral distribution diagram shows four spectral peaks, including one main peak and three secondary peaks. The relaxation time corresponding to the vertex is 1.047 ms, of which the main peak accounts for 85.588%. To more intuitively express the data comparison, the $T_2$ spectrum distributions under the other incorporation ratios are listed in Table 4 below.

It can be seen from Figure 17 that with the increase in the glass fiber incorporation ratio, the $T_2$ spectrum curve shifts to the left to a certain extent. When the incorporation ratio is...
0% and 0.8%, the relaxation times corresponding to the top of the first spectrum peak are the same (1.047), but the peak area at a ratio of 0.8% is larger than that at a ratio of 0%, indicating that when the fiber ratio reaches 0.8%, the pores in the soil sample are damaged due to the excessive glass fiber content. The fibers are intertwined into a group, which leads to the increase of pores, which in turn affects the mechanical properties of the soil. The relaxation time of the peak top of the T2 spectrum curve at ratios of 0.2%–0.6% is consistently 0.912, and the relaxation time is less than the relaxation time in the case of 0% and 0.8% ratios. This indicates that at glass fiber ratios in the range of 0.2%–0.6%, the loess particle-fiber interface is well bonded, and due to the reinforcement effect of the fibers, it can effectively control the development of cracks in the soil sample, "sew" the cracks, and reduce the pores around the cracks.

In summary, at fiber ratios of 0.2%–0.6%, the incorporation of glass fiber has a good inhibitory effect on the pores. At a ratio of 0.8%, however, larger voids are formed in the soil sample due to the excessive incorporation. Therefore, larger pores are formed in the soil sample, which in turn affects its mechanical properties. This conclusion is consistent with the results of the quantitative analysis of the SEM experiments.

### 4. Analysis of the Bonding Mechanism of the Glass Fiber-Modified Loess Interface

According to the bonding mechanism of the good bonding area in the linear fiber bonding model proposed by Naaman et al. [35] and Mechanical and Tribological Properties Theory proposed by Sivamaran et al. [36], when the modified loess is under load, the load is transferred from the soil to the glass fibers, and then the loess-glass fiber interface bears the load. The loess-glass fiber interface is subjected to force analysis to study the bonding mechanism, as shown in Figure 18.

If C is the perimeter of the fiber cross-section, ρ is the local shear stress in the glass fiber-loess interface area, and F is the local force on the glass fiber at x, then, from the force balance:

\[ dF = C \rho dx. \]

After the transformation of formula (6),

\[ \frac{dF}{dx} = C \rho \]

\[ \tau = kS, \]

where, k is a constant function, S is the slip, and the positioning formula is

\[ S = (\delta_f - \delta_s) = \int_0^x [\varepsilon_f(x) - \varepsilon_s(x)] dx. \]

In the above formula, \( \delta_f \) and \( \delta_s \) are the interfacial local displacements of the glass fiber and loess, respectively, and \( \varepsilon_f \) and \( \varepsilon_s \) are the local strains of the glass fiber and loess, respectively.

The local strain of the glass fiber, the fiber cross-sectional area, and the elastic modulus are \( \varepsilon_f, A_f, \) and \( E_f \), respectively. Then, the relationship between the local force F and the local strain \( \varepsilon_f \) is:

\[ F = A_f E_f \varepsilon_f. \]

Similarly, the local force of the soil in the interface area is denoted as G and the cross-sectional area and elastic modulus as \( A_s \) and \( E_s \), respectively. Then, the local force of the soil in the interface area is

\[ G = A_s E_s \varepsilon_s. \]

Then, the calculation formula of the total force T received by the free end of the glass fiber is

\[ T = F + G. \]

It can be derived from the above formula,

\[ \frac{d^2F}{dx^2} = Ck(\varepsilon_f - \varepsilon_s), \]

\[ \frac{d^2F}{dx^2} = -KT + KQF(x). \]

### Table 4: Distribution of peaks in the T2 spectrum with different fiber ratios.

| Incorporation ratio (%) | Spectral peak start and end relaxation time (ms) | Spectral peak share (%) |
|-------------------------|-----------------------------------------------|-------------------------|
|                         | Spectrum peak 1 | Spectrum peak 2 | Spectrum peak 3 |
| 0.2                     | 0.425–4.199 (87.433) | 4.501–33.701 (11.624) | 36.123–102.341 (0.943) |
| 0.4                     | 0.425–4.199 (85.096) | 4.501–41.504 (14.085) | 44.488–77.526 (0.817) |
| 0.6                     | 0.396–4.501 (87.682) | 4.824–29.332 (12.062) | 36.123–102.341 (0.256) |
| 0.8                     | 0.523–4.199 (77.588) | 4.501–33.701 (20.438) | 36.123–95.477 (1.974) |

![Figure 18: Force diagram of a microelement section.](image-url)
The parameters in formula (13) are defined as:

\[ K = \frac{Ck}{A_sE_s}, \]

\[ Q = 1 + \frac{A_sE_s}{A_fE_f}. \] (14)

Let \( \lambda = \sqrt{KQ} \), the solution of formula (13) is:

\[ F(x) = T(C_1e^{kx} + C_2e^{-\lambda x}) + \frac{T}{Q}. \] (15)

Boundary conditions can then be substituted to solve for \( A', B' \), .

\[ C_1 = \frac{1}{1 - e^{-2\lambda l}} \left[ \left( 1 - \frac{1}{Q} \right) e^{-\lambda l} + \frac{1}{Q} e^{-2\lambda l} \right], \]

\[ C_2 = \frac{1}{1 - e^{-2\lambda l}} \left[ \left( 1 - \frac{1}{Q} \right) e^{-\lambda l} + \frac{1}{Q} \right]. \] (16)

By substituting various parameters into \( C_1, C_2 \),

\[ F(x) = (C_1e^{kx} + C_2e^{-\lambda x} + \frac{1}{Q})T, \]

\[ \tau = \frac{dF(x)}{dx} = \left( \frac{C_1kC}{C} - \frac{C_2\lambda e^{-\lambda x} + \frac{1}{CO}}{C} \right)T. \] (17)

From the above formula, the critical value can be solved, and then the critical slip relationship of the glass fiber-loess interface can be obtained as

\[ s_{cr} = \int_0^1 \left( \epsilon - \epsilon_s(x) \right) dx = \frac{(Q - 2)}{\lambda A_sE_s} \left( \frac{1 - e^{-\lambda l}}{1 + e^{-\lambda l}} \right). \] (18)

5. Conclusion

Through the macroscopic mechanical test and microscopic analysis of the modified loess mixed with glass fiber, the following conclusions can be drawn:

1. Glass fiber can be used as an improvement material for loess, which can effectively improve the shear resistance of loess, play a "reinforcing" role and effectively connecting the soil at both ends of cracks.

2. The shear strength of glass fiber-modified loess at increasing confining pressures showed a trend of increasing first and then decreasing. The stress-strain curves all showed hardening. The cohesion first increased and then decreased with the increasing ratio of glass fibers. With the increase in the fiber length, there is a continuous increasing trend; the optimum incorporation ratio is 0.6%, and the optimum length of the glass fiber used in the project is 9 mm.

3. From the qualitative results of low-magnification SEM, it can be concluded that with the increase in the glass fiber incorporation ratio, more cracks were penetrated by the glass fiber and there was a more obvious reinforcement effect. However, when the incorporation ratio reaches 0.8%, the fibers are entangled and intertwined into clusters. The appearance of a large number of through-connected overhead pores causes the strength of the improved soil to decrease. It can be seen from the high-magnification qualitative analysis that with the increase in the glass fiber incorporation ratio, the bonding effect of the glass fiber-loess interface area increases, and the mode of contact between soil particles gradually changes from unstable point-to-point contact to point-edge contact. Edge-to-edge, edge-to-surface and surface-to-surface contact are all observed, but when the mixing ratio is 0.8%, some glass fibers are not in contact with soil particles due to the appearance of overhead pores in the interface area, so the strength drops sharply.

4. The quantitative results of SEM showed that the porosity of the cut surface first decreased and then increased with the incorporation of glass fibers. The pore area in the lower part accounts for the largest proportion, and the NMR tests also draw consistent conclusions, which further verifies the accuracy of the quantitative analysis results.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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