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*Research Article*

# Experimental Study on the Strength Characteristics of Expansive Soils Improved by the MICP Method

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Microbially induced calcite precipitation (MICP) has been a promising method to improve geotechnical engineering properties; however, there are few literatures about the application of the MICP method to improve the strength characteristics of expansive soils with low permeability. In this paper, a series of CD triaxial tests were carried out to investigate the effect of the MICP method on the strength characteristics of the expansive soils. The results show that the shear strength of the specimens increased with the increase in the cementation solution and eventually reached a stable value. The MICP method can significantly improve the shear strength index of the expansive soils. The cohesion of the expansive soils was increased from 29.52 kPa to 39.41 kPa, and the internal friction angle was increased from 20.13° to 29.58°. The stress-strain curves of expansive soil samples improved by the MICP method show a hyperbolic relationship, which is characterized by strain hardening. The hyperbolic model was chosen to describe the stress-strain relationship of the expansive soils improved by the MICP method, and the predicted results were in good agreement with the measured results. Moreover, we performed a scanning electron microscope (SEM) experiment and revealed the mechanism of the MICP method to improve the strength characteristics of expansive soils. The conclusions above can provide a theoretical basis to further study the strength characteristics of improved expansive soils by the MICP method.

## 1. Introduction

Expansive soil is a low-permeability clay soil. It swells significantly after absorbing water and shrinks significantly after losing water. Engineering projects built in areas with expansive soils often suffer from roadbed subsidence and slope instability, leaving potential safety hazards for the construction of the project [1]. In engineering construction, it is usually necessary to mix a certain proportion of lime, cement, fly ash, and fiber to improve the expansive soils [2–4]. The above-mentioned traditional methods of expansive soil improvement are very mature and have been widely used in engineering construction. However, in the process of improvement, there are problems such as higher costs, high labor intensity, long construction period, and environmental pollution [5]. Therefore, there is an urgent need for the academic and engineering communities to find a more economical, efficient, and environmental method to improve expansive soils.

In the last decade, with the development of environmental geotechnics [6–10], the microbially induced calcite precipitation (MICP) method has been widely used in engineering fields such as foundation reinforcement [11], dust and sand consolidation [12], and concrete fracture repair [13, 14]. Research shows that the rock and soil mass contain large amounts of free metal ions [15, 16]. The MICP method involves the use of urease enzymes produced during microbial metabolism to catalyze the hydrolysis of urea to produce carbonate ions, which combine with calcium ions in the surrounding environment to produce calcium carbonate precipitates (which solidify into calcite crystals). Calcium carbonate precipitation not only fills the voids between soil particles but also forms a gel on the surface of soil particles, which makes effective connections between soil particles and makes them coalesce and grow larger [17].

In the early days of MICP method development, scholars mainly applied the MICP method to improve higher permeability sandy soils in the field of geotechnical engineering and achieved many useful research results [18–21], which also greatly promoted the development of environmental geotechnical technology. However, due to the low permeability of clayey soils, the bacteriological solution and cementation solution do not easily enter the interior of the soil, and the MICP method is rarely applied to improve and strengthen clayey soils. In recent years, in order to promote the application of microbial geotechnical technology to improve clayey soils with low permeability, some scholars have also started to apply the MICP method to improve clayey soils with low permeability. Islam et al. [22] selected four soil samples with different plasticity indices and three artificially mixed soil samples with different clay particle contents to investigate the plasticity indices and clay particle contents on the effect of the MICP method on soil improvement. The results show that the MICP method can improve the engineering properties of low-permeability cohesive soils, and the method is considered a promising new technique for improving soft clay soils. Liu et al. [23] demonstrated that the MICP method can effectively improve the strength of loess by unconfined compressive strength tests and scanning electron microscope tests and found that the reaction temperature, concentration of bacterial solution, and cementation solution would affect its improvement effect. Tiwari et al. [24] investigated the effect of the MICP method on the improvement of swelling properties and strength properties of expansive soils. It was found that after modification by the MICP method, the content of calcite increased by 205%, which improved the unconfined compressive strength and splitting tensile strength of expansive soils, and the expansion force and expansion strain decreased significantly. Li et al. and Jiang et al. [25, 26] investigated the physical properties, liquid-plastic limit, and swelling rate of the MICP method for improving expansive soils. In order to overcome the problem of low permeability of expansive soils, where the bacterial solution and the cementation solution could not easily enter the interior of the soil, the bacterial solution and the cementation solution were mixed into the expansive soil separately by using the mixing method. It was found that the hydrophilic capacity of the improved expansive soil was significantly weakened, and the corresponding water absorption swelling rate and water loss shrinkage rate were significantly reduced. After improvement by the MICP method, medium expansive soils become nonexpansive soils.

In summary, the application of the MICP method to improve expansive soils with low permeability is still at a preliminary stage of exploration. In order to promote the application of biotechnology in the field of geotechnical engineering and to develop the theory and technology related to the improvement of expansive soils by the MICP method, it is necessary to conduct more in-depth research in this field.

Therefore, this paper researches the effect of the cementation solution on the strength characteristics of the improved expansive soils using the MICP method. The strength of the improved expansive soils was investigated with a series of CD triaxial tests. The influence law of the cementation solution on the ultimate partial stress and shear strength index of the soil was investigated. At the same time, the stress-strain relationship of the expansive soils by the MICP method was described using a hyperbolic model. Moreover, scanning electron microscope imaging (SEM) tests were conducted on the specimens to reveal the mechanism of the MICP method to improve the strength characteristics of expansive soils.

## 2. Materials and Methods

*2.1. Test Material.* The expansive soils used in the experimental study come from Guangxi. The soil is scaly, mainly off-white, slippery, and gravelly to the touch, as shown in Figure 1. The particle size distribution of the expansive soils was obtained by taking the expansive soils for particle analysis tests. Its particle size distribution is shown in Table 1. The optimal water content and maximum dry density of the fill material were determined by the heavy compaction test, and the indicators of each physical property of the expansive soils are shown in Table 2.

*2.2. Cultivation of Microorganisms.* The microorganism used in our experimental study is *Bacillus pasteurii* with strain number ATCC11859, which was purchased through the China National General Microbial Species Collection Management Center (CGMCC). This bacterium is isolated from natural soil and is harmless to humans and other organisms and can produce large amounts of urease during its life activity [27]. The inoculated bacterial solution is incubated in a smart shaker at a temperature of 30°C and a shaker speed of 150 r/min for 36 hours. The concentration of the bacterial solution is usually expressed by the absorbance $OD_{600}$ value, and it can be used for the test when the $OD_{600}$ value of it is just greater than 1.0 [25].

*2.3. Preparation of Cementation Solution.* Natural expansive soils have a low content of calcium elements and thus have a low calcium carbonate yield during microbial mineralization. Therefore, the calcium source needs to be supplemented by the addition of a cementation solution in the experimental study. The cementation solution is a mixture of urea $[CO(NH_2)_2]$ and calcium chloride ($CaCl_2$). During the MICP biochemical reaction, bacteria can produce large amounts of urease in an alkaline environment. Urease catalyzes the hydrolysis of urea to produce carbonate ions. Calcium chloride acts as a calcium source to provide the required free calcium ions during the MICP reaction. The carbonate ions and calcium ions are chemically combined to form calcium carbonate precipitates. It has been shown that the molar concentration of the cementation solution should not exceed 1 mol/L when calcium chloride is used as the calcium source [27–29]. Therefore, the molar concentration of the cementation solution was finally determined to be 1 mol/L. The molar ratio of urea to calcium chloride was determined to be 1 : 1 based on the chemical calculations of the MICP reaction process.

*2.4. Specimen Preparation.* Firstly, the expansive soils were air-dried. Then, the bacterial solution was sprayed into the particles which passed through 2 mm sieve in layers. After

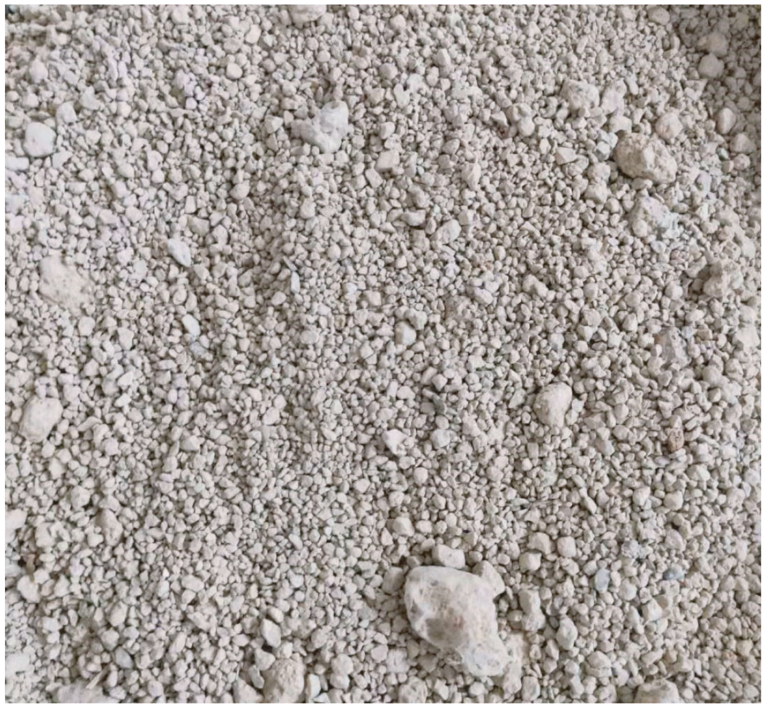


Figure 1: Expansive soils used for the study.

mixing well, the cementation solution is then mixed evenly into the expansive soils in the same way. The mixed expansive soils were sealed with cling film, leaving some pores to ensure the oxygen supply required for bacterial growth. Subsequently, the soil samples were placed in a constant temperature and humidity biochemical incubator and maintained for 7 days. After completion of maintenance, the soil samples were air-dried at an accelerated rate until their moisture content reached the optimum moisture content required for maximum compaction (16.2%). The air-dried soil samples were placed in a humidifying cylinder and stewed for 24 h. After stewing, a mold with a height of 80 mm and a diameter of 39.1 mm was selected, and the soil samples required for each specimen were poured into the mold in five portions and compacted in five layers. After the specimen was formed, the specimen was saturated by a vacuum saturation pumping method.

*2.5. Testing Schemes.* This test adopted a strain-controlled GDS triaxial shear apparatus equipped with data acquisition and control systems to carry out consolidation and drainage shear (CD) tests. The GDS triaxial test system is shown in Figure 2. The bacterial solution (with contents of 50 mL) and cementation solution (with contents of 50 mL, 75 mL, 100 mL, and 125 mL, respectively) were mixed into the expansive soils to explore the effects of MICP reinforcement on the strength characteristics. In this study, one group of unimproved soil specimens and four groups of MICP reinforcement soil specimens were conducted. During the tests, the applied confining pressure was 50 kPa, 100 kPa, 200 kPa, or 300 kPa, and the shear rate was 0.04 mm/min. When the axial strain reached 15%, the test was stopped. The specific test scheme is shown in Table 3.

Table 1: Particle size distribution of expansive soils.

| ≤0.005 | (0.005,0.075] | (0.075,0.025] | (0.025,0.5] | (0.5,2] | (2,20) |
|---|---|---|---|---|---|
| 15.2 | 62.5 | 7.3 | 6.8 | 5.4 | 2.8 |

## 3. Results and Discussion

*3.1. Stress-Strain Curve of the Specimens.* The relationships between the axial strain $\varepsilon_1$ and the partial stress ($\sigma_1$ - $\sigma_3$) of the soil samples under different colloid admixtures and different confining pressure conditions are shown in Figure 3.

From Figure 3, it can be found that when the specimens with the same cementation solution reach the same axial strain under different confining pressures, the partial stresses increase with the confining pressures. When the axial strain is small, the stress-strain curves of unimproved expansive soil specimens and improved expansive soil specimens basically coincide under the action of different confining pressures. This is because under low strain conditions, the stresses in the soil are both smaller. It can also be found in Figure 3 that the partial stresses of various specimens increase rapidly with the increase in axial strain. After the strain reaches a certain value, the increase in the partial stress gradually decreases and finally they all tend to stabilize. The stress-strain curves of various specimens have no obvious peak points and meet an approximate hyperbolic, which reflects the strain hardening characteristics. At the same time, under the same circumferential pressure, the damage partial stress value of the soil sample increases with the increase in the cementation solution. And it was found that the damage partial stress value reached the maximum

Table 2: Basic physical properties of soil samples.

| Soil source | Natural density (g/cm$^3$) | Maximum dry density (g/cm$^3$) | Gs | $W_L$ (%) | $W_p$ (%) | $I_p$ (%) | OMC (%) | Free swelling rate (%) |
|---|---|---|---|---|---|---|---|---|
| Nanning | 1.88 | 1.94 | 2.70 | 60.8 | 22.4 | 38.4 | 16.2 | 61.3 |

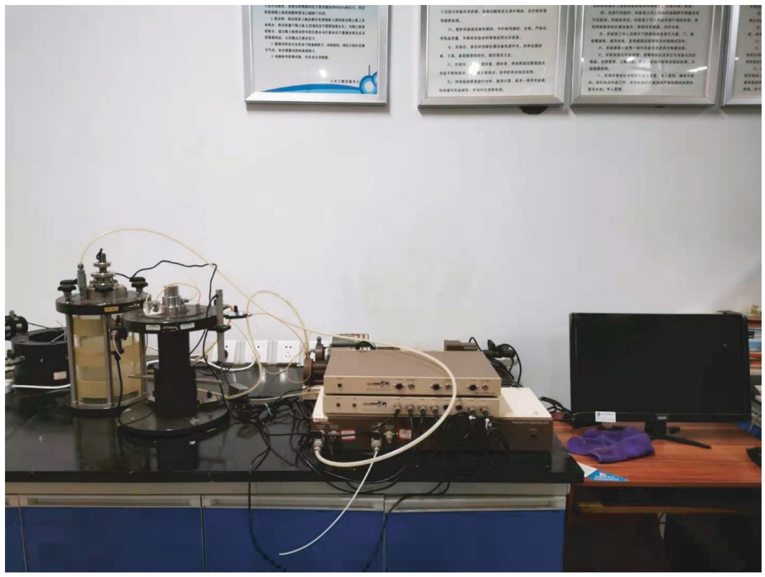


Figure 2: GDS triaxial testing system.

Table 3: Triaxial consolidation and drainage shear test scheme.

| Bacterial solution (mL) | Cementation solution (mL) | Quality of expansive soils (g) | Confining pressure (kPa) | Degree of compaction (%) |
|---|---|---|---|---|
| 50 | 50, 75, 100, 125 | 500 | 50, 100, 200, 300 | 90 |
| 0 | 0 | 500 | 50, 100, 200, 300 | 90 |

value when the cementation solution was 125 mL. According to the theory of soil mechanics, it is known that the relationship between the shear strength of soil and the damage deflection stress is that

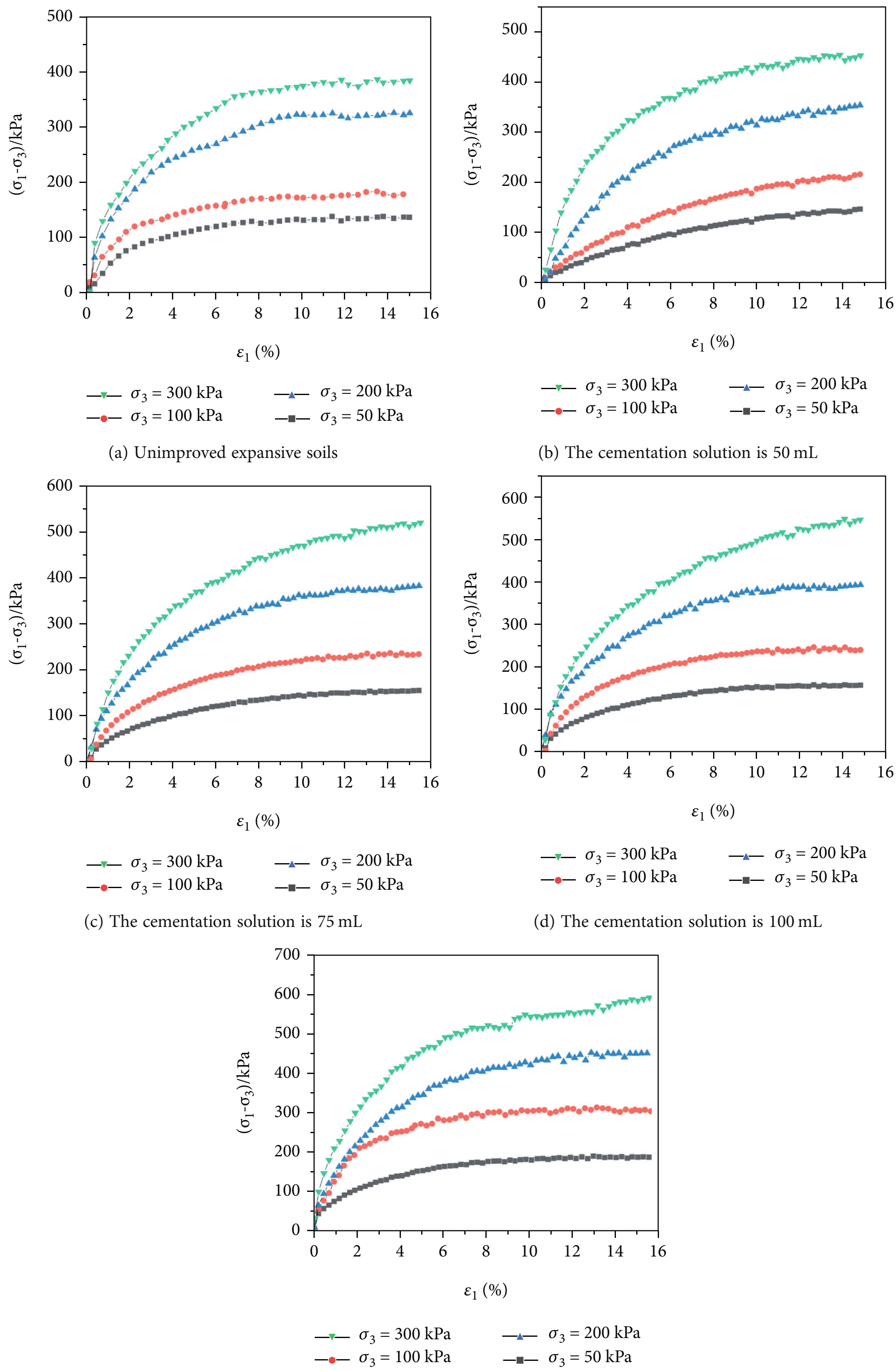
$$\tau_f = \frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\alpha. \quad (1)$$

In equation (1), $\tau_f$ is the shear strength of the soil and $\alpha$ is the angle between the shear rupture surface and the $\sigma_3$ action surface.

*3.2. Variation of Damage Deflection Stress.* Based on the triaxial consolidation drainage shear test of the specimens, the damage bias stresses of various specimens can be obtained, as shown in Figure 4.

From Figure 4, it can be found that the damage partial stress (shear strength) of the improved expansive soils increased with the cementation solution, but the increments gradually decreased while the shear strength tended to be in a stable value under the same confining pressure. With 50 mL, 75 mL, 100 mL, and 125 mL of cementation solution, the damage partial stress of the improved expansive soil specimens increased by 6.79%, 23.77%, 29.91%, and 38.49% under the condition of 50 kPa confining pressure, respectively. Similarly, the damage partial stresses increased by 18.05%, 28.90%, 41.99%, and 71.05% at a confining pressure of 100 kPa, respectively. At a confining pressure of 200 kPa, the damage partial stresses increased by 16.52%, 25.92%, 29.95%, and 49.14%, respectively. The damage partial stresses increased by 14.66%, 31.23%, 38.63%, and 53.24% at a confining pressure of 300 kPa, respectively. The above conclusions indicate that the shear strength of the expansive soils improved by the MICP method increases with the cementation solution and eventually converges to a certain stable value. On the other hand, we can see that the shear strength of the improved expansive soils increases with the confining pressure for the same cementation solution from both Figure 4 and equation (1). Obviously, this proves that the expansive soils improved by the MICP method still meet the Mohr-Coulomb strength criterion.

*3.3. Variation of Shear Strength Index.* The Mohr-Coulomb strength envelope of the soil sample under the condition of




(a) Unimproved expansive soils

(b) The cementation solution is 50 mL

(c) The cementation solution is 75 mL

(d) The cementation solution is 100 mL

(e) The cementation solution is 125 mL

Figure 3: Relations between $\varepsilon_1$ and $(\sigma_1\text{-}\sigma_3)$ of expansive soil samples.

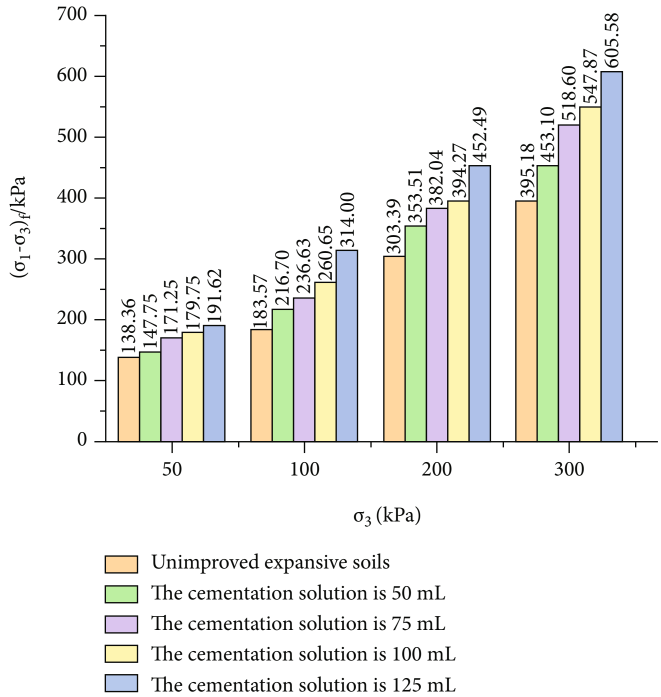



Figure 4: Ultimate deviatoric stresses of soil samples.

the cementation solution is the tangent line of the above Mohr circle. According to the Coulomb shear strength theory, there is that

$$\tau_f = c + \sigma \tan \varphi. \quad (2)$$

According to equation (2), the cohesion and internal friction angle of the soil specimens can be calculated under various conditions of different cementation solutions. The effect of the cementation solution on the cohesion and internal friction angle of the soil specimens is shown in Figure 5.

From Figure 5, it can be found that the cohesive force and internal friction angle of the improved expansive soils were significantly increased with the increase in the cementation solution. Compared with the unimproved expansive soils, the cohesive force of the improved expansive soils increased from 29.52 kPa to 39.41 kPa, with an increase of 33.5%. Its internal friction angle increased from 20.13° to 29.58°, with an increase of 46.94%.

The results of the triaxial shear test showed that the cohesion and internal friction angle of the expansive soils were significantly improved after the improvement by the MICP method. This led to a significant increase in the shear strength of the improved expansive soils. The underlying reason is that the microbially induced formation of calcium carbonate precipitates cemented the soil particles and filled the soil pores. When the calcium carbonate precipitation solidified, it turned into calcite crystals, which made the soil particles cohesive and coarser, and the interparticle connection was stronger, and the compactness of the soil was improved. As a result, the microstructure of the soil is significantly changed.

## 4. Hyperbolic Model for Improved Expansive Soils by the MICP Method

From the above discussion, it is clear that the strength characteristics of the MICP method for improving expansive soils are most significant at 125 mL of cementation solution. Meanwhile, for the strain-hardening type stress-strain curve shown in Figure 3, it can be fitted with a hyperbolic function [30]. Therefore, in this paper, the hyperbolic model is chosen to describe the stress-strain relationship for the improved soil specimens under 125 mL of cementation solution.

According to the proposal of Kondner, the stress-strain relationship of soil was expressed by the hyperbolic model as [31]

$$\sigma_1 - \sigma_3 = \frac{\varepsilon_1}{a + b\varepsilon_1}. \quad (3)$$

With $\varepsilon_1$ as the horizontal coordinate and $\varepsilon_1/(\sigma_1 - \sigma_3)$ as the vertical coordinate, the hyperbolic equation represented by equation (3) can be converted into a linear equation, as shown in equation (4).

$$\frac{\varepsilon_1}{\sigma_1 - \sigma_3} = a + b\varepsilon_1. \quad (4)$$

In equations (3) and (4), $(\sigma_1 - \sigma_3)$ is the partial stress, $\varepsilon_1$ is the axial strain, and $a$ and $b$ are test parameters.

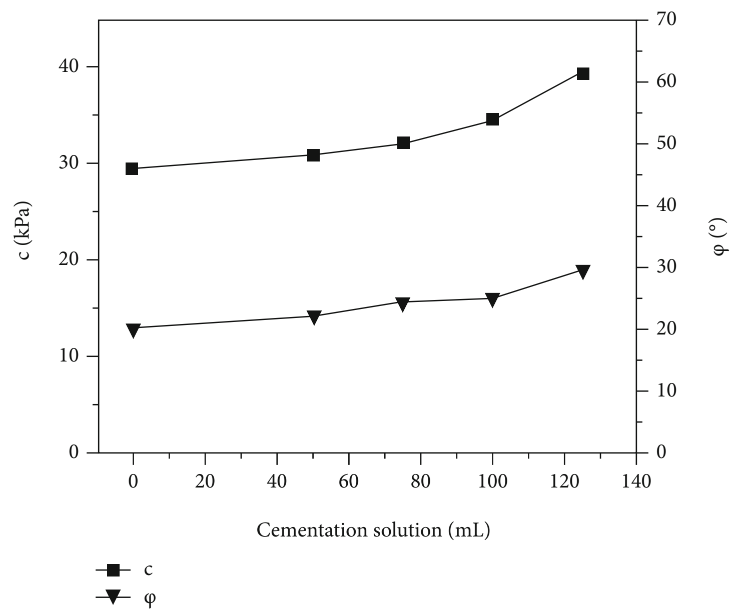



Figure 5: The effects of cementation solution on the $c$ and $\varphi$.

Table 4: Hyperbolic model parameters.

| Cementation solution | $\sigma_3$ (kPa) | $a$ | $b$ | $E_i$ ($\times 10^3$ kPa) | $(\sigma_1 - \sigma_3)_{ult}$ (kPa) |
|---|---|---|---|---|---|
| 125 mL | 50 | 0.0085 | 0.0047 | 11.79 | 215.05 |
| | 100 | 0.0040 | 0.0029 | 24.94 | 342.47 |
| | 200 | 0.0049 | 0.0019 | 20.58 | 537.63 |
| | 300 | 0.0033 | 0.0015 | 30.49 | 684.93 |

According to taking the derivative of equation (3) and eliminating, tangent elastic modulus can be expressed as

$$E_i = \frac{1}{a}[1 - b(\sigma_1 - \sigma_1)]^2 = E_i\left[1 - \frac{(\sigma_1 - \sigma_3)}{(\sigma_1 - \sigma_3)_{ult}}\right]^2. \quad (5)$$

In equation (5), $E_i$ is the initial tangent modulus and $(\sigma_1 - \sigma_3)_{ult}$ is the ultimate deviant stress.

From equations (3) and (4), the parameters have a clear physical meaning. $a$ is the intercept of the linear equation, which corresponds to the reciprocal of the initial tangent modulus in the stress-strain curve, and can be expressed as

$$a = \frac{1}{E_i}. \quad (6)$$

$b$ is the slope of the linear equation, which corresponds to the reciprocal of the ultimate partial stress in the stress-strain curve, and can be expressed as

$$b = \frac{1}{(\sigma_1 - \sigma_3)_{ult}}. \quad (7)$$

Based on the results of the triaxial tests, the parameters $a$ and $b$ were obtained by calculation. The calculation results are shown in Table 4.

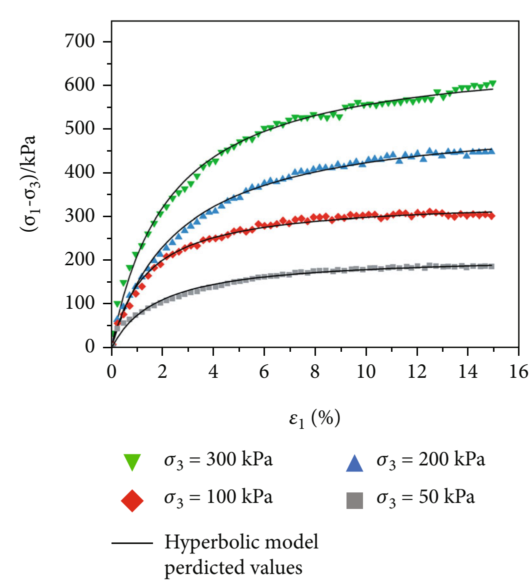
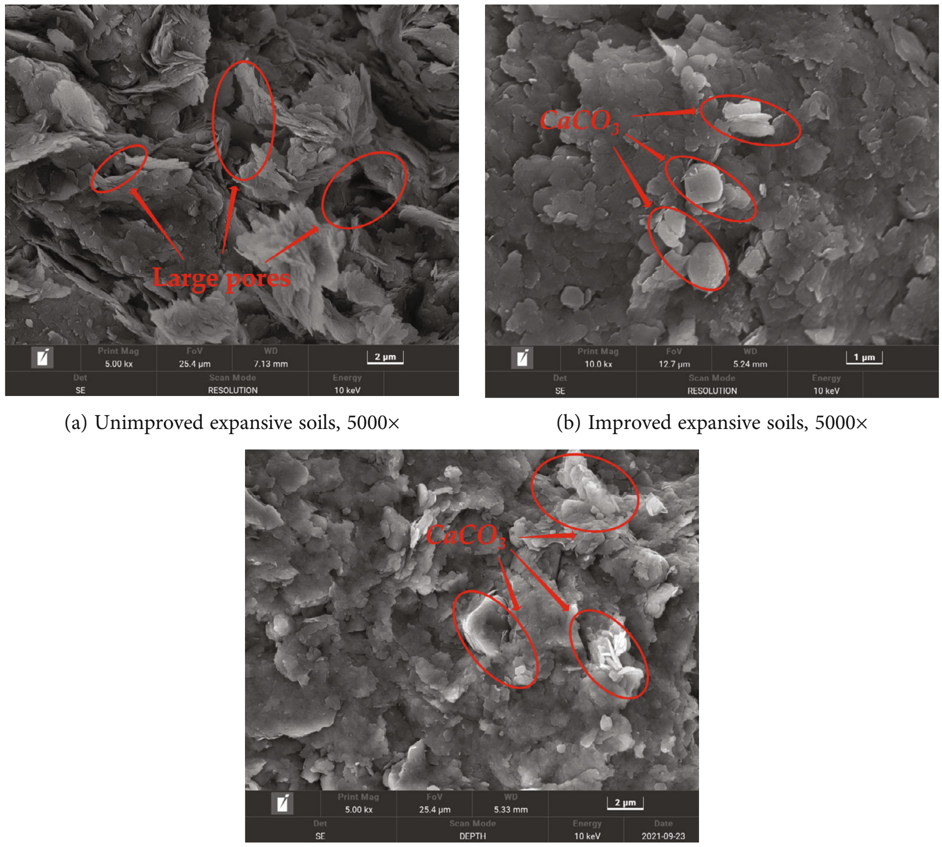



Figure 6: Comparison of fitted results and measured results.

To verify the applicability of the hyperbolic model describing the MICP method for improving expansive soils, the stress-strain relationship was predicted for the specimens with 125 mL of cementation solution. A comparison of the predicted results with the measured results is shown




(a) Unimproved expansive soils, 5000×

(b) Improved expansive soils, 5000×

(c) Improved expansive soils, 10000×

Figure 7: SEM micrographs.

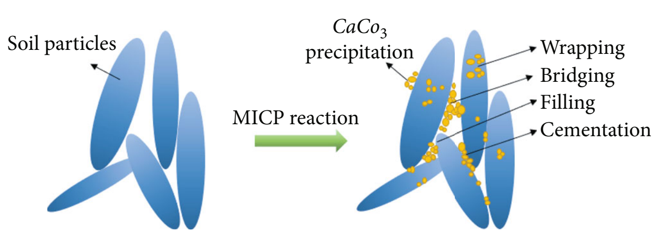



Figure 8: Mechanism of the MICP method improves strength characteristics of expansive soils.

in Figure 6. From Figure 6, it can be found that the stress-strain curve fitted by the hyperbolic model agrees well with the experimental results.

## 5. Microscopic Mechanism Analysis

In order to reveal the improvement mechanism of the strength characteristics of the expansive soils by the MICP method, the microstructural characteristics of the expansive soil specimens improved by the MICP method under the conditions of unimproved expansive soils and 125 mL of cementation solution were analyzed by a scanning electron microscope (SEM) imaging technique. The SEM images of the expansive soils before and after the improvement are shown in Figure 6.

From Figure 7(a), it can be found that the unimproved expansive soil contains a large number of monolithic clay particles which form agglomerates between units. The soil particles of the unimproved expansive soils have large pores, and the large pores between the aggregates are particularly prominent. There are also many dispersed fine particles on the agglomerates with a looser structure. From Figure 7(b), compared with the unimproved expansive soil, the large pores on the surface of the soil improved by the MICP method are greatly reduced, and the soil structure is more compact and the integrity becomes stronger. As a result, the shear strength of the soil sample was increased. The soil particles improved by the MICP method are surrounded by angular crystals, which are calcium carbonate precipitates produced by microbial mineralization. During the mineralization process, the calcium carbonate precipitates were deposited between the soil particle voids, and adjacent calcium carbonate precipitates formed agglomerates due to volume expansion, which played a cementing and filling role for the soil particles. From Figure 7(c), when calcium chloride is used as the calcium source, the MICP reaction produces calcium carbonate precipitates in cubic crystals. The calcium carbonate precipitation adheres to the surface of soil particles, which increases the roughness of the surface of soil particles, leading to an increase in the interlocking effect [32, 33] between soil particles, thus increasing the occlusion force between soil particles [28].

The mechanism of the strength characteristics of MICP method-improved expansive soils is shown in Figure 8. From Figure 8, it can be more intuitively found that the calcium carbonate precipitation generated by the MICP biochemical reaction plays four main roles, which are wrapping, bridging, filling, and cementation. The wrapping effect refers to the fact that calcium carbonate precipitation wrapped around the particle surface increases the roughness of the soil particle surface, which increases the occlusion force between the soil particles and thus increases the internal friction angle of the soil sample. Bridging effect means that as the calcium carbonate content increases, more and more calcium carbonate precipitates gather and form calcium carbonate agglomerates until they link the soil particles. Filling action means that calcium carbonate precipitation fills the voids between soil particles, making the soil denser, thus improving the shear strength of the soil sample. The cementation effect refers to the aggregation of calcium carbonate precipitation near the contact point of soil particles, which binds the soil particles in contact with each other.

## 6. Conclusions

At present, most of the studies on the MICP method for soil consolidation have focused on sandy soils with high permeability. However, few literatures were about applying the MICP method to improve expansive soils with lower permeability which have been reported in related articles. In this research, the following conclusions were obtained using the MICP method to improve the expansive soils and comparing the microstructure of the expansive soils before and after the improvement.

(1) The stress-strain curves of the MICP method-improved expansive soil specimens had no obvious peak points and showed an approximate hyperbolic relationship, which reflected the strain hardening characteristics. At the same time, the shear strength of the soil sample at the time of damage increases with the increase in the cementation solution under the condition of the same confining pressure and finally converges to a certain stable value

(2) The cohesion and internal friction angle of the improved expansive soil increased with the cementation solution. After microbial modification, the cohesive force of the expansive soil increased from 29.52 kPa to 39.41 kPa, with an increment of 33.5%. Its internal friction angle increased from 20.13° to 29.58°, with an increment of 46.94%

(3) The stress-strain relationship of the expansive soils improved by the MICP method can be represented by a hyperbolic function, and the stress-strain curve fitted by the hyperbolic model agrees well with the experimental results

(4) The microstructural analysis revealed the mechanism of the MICP method to improve the strength characteristics of expansive soils. The calcium carbonate precipitates generated by the MICP biochemical reaction mainly acted as wrapping, bridging, filling, and cementation, which led to a significant increase in the shear strength of the soil specimens

The above conclusions indicate that the strength of expansive soils can be effectively improved by the MICP method. In practical applications, the long-term strength of the MICP method for improving expansive soils, especially the durability performance under special environmental conditions, deserves further study.

## Data Availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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