Experimental Study on Microstructure of Unsaturated Expansive Soil Improved by MICP Method

Xinpei Yu 1, Hongbin Xiao 1,*, Zhenyu Li 1, Junfeng Qian 2, Shenping Luo 1 and Huanyu Su 1

1 School of Civil Engineering, Central South University of Forestry and Technology, Changsha 410018, China; 20191100320@csuft.edu.cn (X.Y.); 13787024735@163.com (Z.L.); 20191100323@csuft.edu.cn (S.L.); 20201100370@csuft.edu.cn (H.S.)
2 Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia; junfeng.qian@monash.edu
* Correspondence: t20090169@csuft.edu.cn; Tel.: +86-135-7482-6532

Abstract: The soil water characteristic curve and microstructure evolution of unsaturated expansive soil improved by microorganisms in Nanning, Guangxi were studied by means of filter paper method and scanning electron microscope imaging (SEM). Based on Fredlung & Xing model, the influence law of different cement content on the soil water characteristic curve of improved expansive soil is proved. According to the analysis of SEM test results, the influence mechanism of MICP method on the engineering characteristics of improved expansive soil is revealed. The results show that with the increase of cement content, the saturated water content and residual water content of the improved expansive soil gradually increased. At the same time, the water stability gradually increased while the air inlet value gradually decreased. The improved expansive soil changes from the superposition of flat particles and flake particles to the contact between spherical particles and flake particles, which indicates that the aggregate increases significantly. With the increase of the content of cement solution, the contact between particles tends to be smooth and the soil pores gradually tend to be evenly distributed. The particle size and microstructure of soil particles was changed and the connection between particles was enhanced in the improved expansive soil. Eventually the strength and water stability of expansive soil were improved. The conclusions above not only provide a theoretical basis for the in-depth study of engineering characteristics of unsaturated expansive soil improved by MICP method, but also offer theoretical evidence for perfecting engineering technology of expansive soil improved by MICP method.

Keywords: microbially induced carbonate precipitation (MICP); unsaturated soil; soil-water characteristic curves; matrix suction; microstructure

1. Introduction

Expansive soil is special catastrophic clay composed of strong hydrophilic minerals such as montmorillonite, illite, and kaolinite, which usually exhibit significant over-consolidation, multiple fissures, and swell-shrink characteristics. Expansive soils are distributed in a wide range in China and exist to varying degrees in more than 20 provinces such as Guangxi, Yunnan, and Sichuan. After expansive soil is exposed to water, it is highly susceptible to swelling deformation, softening and strength decay, and dry shrinkage cracks when water is lost. This repeated expansion and contraction deformation will lead to crack, subgrade uplift and slope sliding which will cause major engineering disasters [1–3]. Therefore, any construction work in expansive soil area must be treated and improved to eliminate potential engineering hazards. Traditional methods widely used in engineering for improving expansive soils are usually divided into physical and chemical improvement methods [4,5]. These methods of improving expansive soil could reduce expansive soil's swell-shrink characteristic effectively and also improve its strength. However, the traditional methods of improvement are not only labor-intensive and time-consuming, but...
also pollute the surrounding environment, and may even have negative impacts on the long-term ecosystem. Therefore, the academic and engineering circles urgently need a new, sustainable, and environmentally friendly alternative method to improve the poor engineering properties of expansive soil.

With the interpenetration of modern biotechnology and engineering science, bio-geotechnical engineering has become a new and hot research field. In recent decades, the Microbially Induced Carbonate Precipitation (MICP) method was used by scholars at home and abroad to repair fractures, seepage control, sand consolidation and soft soil improvement with good results [6–9]. In terms of applying the MICP method to improve the engineering characteristics of soft soils, scholars from home and abroad have mainly researched in improving sandy soils and made great progress [10–14]. In recent years, a few scholars have used the MICP method to improve expansive soil and other soft clays, which has made gratifying research progress. Bai studied the coupled migration of ions in soil [15]. Liu demonstrated that the MICP method can effectively improve the strength of loess through unconfined compressive strength test, calcium carbonate content test and scanning electron microscope test, and found the optimal reaction conditions and cementation liquid content for the improvement [16]. Safdar and Gowthaman studied the MICP method for improving peat soils. It was found that Bacillus licheniformis was more effective in improving peat soils, and that scallop powder was effective in increasing the activity of microorganisms and promoting the cementation of peat soil particles [17,18]. Some scholars investigated the swelling properties, strength properties, and microstructure of MICP modified expansive soils through a series of tests such as one-dimensional swelling tests, tensile tests, consolidation tests and compression tests. The MICP method of improved expansive soils can control the swelling and shrinking characteristics of the soil and improve the strength of the soil, and the calcite produced by the reaction can also provide a linkage to the soil particles [19–21]. Expansive soil in nature is usually unsaturated. Based on the theory of unsaturated soil mechanics, scholars carried out research on the engineering properties of unsaturated soil [22–26]. Soil-water Characteristic Curves (SWCC) obtained from unsaturated soil tests can be used to study the hydrophilicity, swell-shrinkage and strength characteristics of expansive soil improved by the MICP method.

In this paper, a series of experimental studies were carried out on expansive soil improved by the MICP method using the filter paper method. The SWCC of the expansive soil was measured after the improvement of different solutions with different cementation liquid content. The relationship between the moisture content of the expansive soil and the matric suction was obtained. Following comparison of four empirical models, Fredlund & Xing model was chosen to analyze the SWCC of the expansive soil after improvement by different schemes. The air entry value and water stability of the expansive soil were obtained.

The particle shape and pore space changes in the improved expansive soil were gotten by Scanning Electron Microscope (SEM) tests. From the perspective of microstructural changes in soil samples, the mechanism of the effect of different cementation liquid content on the water stability and water sensitivity of improved expansive soil during the MICP process was revealed.

2. SWCC Test Materials and Methods
2.1. Test Materials

The expansive soil used in the study was taken from Nanning, Guangxi, and was off-white. The particle size distribution of the unimproved expansive soil was obtained by taking the expansive soil for particle analysis tests. The particle size distribution of the expansive soils, as shown in Table 1.
Table 1. Particle size distribution of expansive soil.

| Particle Size (mm) | Content (%) |
|-------------------|-------------|
| ≤0.005            | 15.4        |
| 0.005~0.075       | 62.9        |
| 0.075~0.25        | 7.1         |
| 0.25~0.5          | 6.9         |
| 0.5~2             | 5.2         |
| >2                | 2.6         |

The obtained expansive soil was dried, crushed, adopted 2 mm sieve and a portion of the particles less than 2 mm in diameter was taken for testing. The basic physical properties of the expansive soil were obtained from the tests and are shown in Table 2.

Table 2. Indicators of physical property of expansive soil.

| Indicator                  | Content (%) |
|----------------------------|-------------|
| Liquid Limit (%)           | 58.1        |
| Plastic Limit (%)          | 22.3        |
| Plastic Index (%)          | 35.8        |
| Natural Moisture Content (%)| 21.8        |
| Optimal Moisture Content (%)| 23.3        |
| Maximum Dry Density (%)    | 1.75        |

2.2. Sample Preparation of MICP Improved Expansive Soil

2.2.1. Bacteria and Culture Media

The microorganism used to improve the expansive soil was Bacillus pasteurii, purchased from the Chinese General Microbial Strain Collection (CGMCC) under the number ATCC11859. This strain is a nonpathogenic, Gram-positive bacteria, which has no adverse effects on humans or the biological environment, a good ability to secrete urease, and is present in natural soil [27]. The Bacillus pasteurii used for the test is shown in Figure 1. The culture medium consisted of 20 g/L urea, 20 g/L agar, 15 g/L casein peptone, 5 g/L soy peptone and 5 g/L sodium chloride. Bacillus pasteurii was inoculated in a slant medium and incubated at 30 °C for 24 h and stored at 4 °C. The culture was inserted into an agar-free medium and incubated for 36–48 h in a constant temperature shaking incubator at a temperature of 30 °C and a speed of 150 r/min. The absorbance $OD_{600}$ value of the bacterial liquid at a wavelength of 600 nm was measured using a spectrophotometer. When the $OD_{600}$≈1.6, the bacterial solution is used to improve the expansive soil.

![Bacillus pasteurii](image)

Figure 1. Bacillus pasteurii used in testing.

2.2.2. Preparation of Cementation Liquid

The cementation liquid is a source of calcium for the MICP process and provides the raw material and hydrolytic environment for the metabolic processes of the microorganisms. Based on the chemical reaction equation for the MICP process, it can be calculated that for every molecule of calcium carbonate produced, 1 molecule of calcium chloride and 1 molecule of urea are required [28]. Therefore, the ratio of calcium chloride to urea in the cementation liquid was determined to be 1:1 and the concentration of the cementation...
liquid was 1 mol/L. Each 100 mL of cementation liquid contained 21.91 g of CaCl$_2$·6H$_2$O and contained 6.01 g of urea.

2.2.3. Preparation of Soil Samples

The soil samples used in the test were divided into four groups, one of which was an unimproved expansive soil as a control group and the other three groups were samples that had been improved using the MICP method. Due to the high liquid limit and low permeability of expansive soil, conventional grouting and soaking methods cannot be used to improve expansive soil by the MICP method. In the tests, the expansive soil was amended by spraying and then mixing. The unimproved expansive soil was mixed with the cementation liquid and the bacterial fluid, respectively, and then kept in a constant temperature and humidity biochemistry cultivation cabinet at 30 °C for 14 days. During the curing process, holes need to be poked in the plastic film to provide the aerobic environment for bacterial metabolism to survive.

2.3. Test Scheme and Procedure

Four sets of tests were set up to investigate the effect of cementation liquid content on the SWCC of expansive soil during MICP. In addition to one group of unimproved expansive soil samples, three other groups of expansive soil samples were successively improved with cementation liquid and bacterial liquid. The improved soil samples were dehumidified and absorbed after 14 days of curing and weighed regularly to make sure they reached the moisture content required for the experimental design. The maximum dry density $\rho_{dm}$ of the expansive soil is taken as the dry density of the specimen and the degree of compaction is 90%. Calculated the mass of loose soil required for the sample and made it into a ring-knife sample of size 61.8 × 20 mm. Based on relevant studies by Jiang [19] and Li [20] on the microbiological improvement of expansive soil, the admixture of cementation liquid and bacterial liquid in the experimental scheme was designed [19]. In the three groups of improved expansive soil samples, the content of cementation liquid was 100, 125, and 150 mL respectively, and the content of bacterial liquid was 50 mL. The test scheme for the MICP method of improving expansive soil is shown in Table 3.

| Total Sample | Sample Number | Bacterial Liquid Content (mL) | Cementation Liquid Content (mL) | Degree of Compaction (%) |
|--------------|---------------|-------------------------------|---------------------------------|--------------------------|
| 112 A1, A2, A3 | 50 | 100, 125, 150 | 90 |

Dried filter paper (“Double Circle” brand, No. 203) is placed between two soil samples and three layers of filter paper are placed in each set of samples. The top and bottom layers are qualitative filter paper with a diameter of 60 mm and the middle layer is quantitative filter paper with a diameter of 50 mm. Use electrical insulation tape to seal the contact surface of the two ring knives, then wrap the test sample in plastic film and then wrap the plastic film tightly with electrical insulation tape. The wrapped samples are placed in the basin, sealed twice using plastic film and placed in a 20 °C thermostat. After 7 days, moisture equilibrium is reached between the filter paper and the expansive soil, at which point the matric suction of the filter paper and the expansive soil can be considered equal. The middle layer of the filter paper is removed with forceps and the mass of the wet filter paper is quickly weighed and recorded.

The test needs to be conducted under three assumptions. Firstly, it was assumed that *Bacillus pasteurii* with consistent absorbance would have the same activity and produce the same urease activity. Secondly, it is assumed that the expansive soils are well mixed during the treatment of the MICP method. Thirdly, it is assumed that the resting specimen is completely sealed during the filter paper method of testing. To ensure the reliability of
the test results and to minimize errors arising during the test, a control group was designed in the experimental study. Measure the matric suction, as shown in Figure 2.

![Figure 2. Measurement for matrix suction: (a) sealed storage; (b) dried filter paper.](Image)

According to the study of the calibration curve of the “double circle” brand filter paper by Bai Fuqing [29] and Zhang Hua [30], the matric suction of the soil sample is determined by using the calibration formula. The calibration result of matrix suction, as shown in Equation (1).

$$
\begin{align*}
\lg(S_m) &= -0.0767\theta_s + 5.493 \quad \theta_s \leq 47\% \\
\lg(S_m) &= -0.0120\theta_s + 2.470 \quad \theta_s > 47\%
\end{align*}
$$

where $S_m$ represents the matrix suction, and $\theta_s$ represents the moisture content of the filter paper after equilibrium.

### 3. Results and Analysis of SWCC Test

#### 3.1. Selection of the SWCC Fitting Model

To facilitate the analysis of the test data, empirical models of SWCC were used to fit the test results. Commonly used SWCC models include the Van Genuchten model (VG model) [31,32], the Gardner model [33] and the Fredlund & Xing model [34]. Among them, the VG model is in two- and three-parameter forms, and the commonly used empirical model equations are as follows.

$$
\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha \phi)^{n}\right]^{(m-1)}}
$$

$$
\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha \phi)^{n}\right]} 
$$

$$
\theta = \theta_r + \frac{\theta_s - \theta_r}{1 + \left(\frac{n}{\phi}\right)^{n}}
$$

$$
\theta = \theta_r + \frac{\theta_s - \theta_r}{\ln\left[1 + \left(\frac{n}{\phi}\right)^{n}\right]}
$$

where $\theta$ represents the soil volumetric moisture content, $\theta_s$ represents the saturated volumetric moisture content, $\theta_r$ represents the residual volumetric moisture content, $e$ represents the base of the natural logarithm and $e \approx 2.71$, $\phi$ represents the matric suction, $\alpha$, $n$, $m$ all represent the fitted parameters.
The four models mentioned above were used to fit the test results of the expansive soils after improvement with different cementation liquid contents. The SWCC was obtained for the improved expansive soils with different fitting models, as shown in Figure 3.

Figure 3. Soil-water characteristic curves obtained by model fitting: (a) fitted curve for unimproved expansive soil; (b) A1 fitted curve; (c) A2 fitted curve; (d) A3 fitted curve.

Figure 3 shows that the SWCC of the expansive soils is anti-“S” shaped after the different solutions. The transition section of SWCC in unimproved expansive soils is relatively steep, the rate of desorption in expansive soils is greater, matrix suction has a greater effect on the volumetric moisture content of the soil and the capacity to hold water is weaker. The transition section of the SWCC of the improved expansive soil tends to flatten out as the admixture of cementation liquid increases, the rate of desorption gradually decreases and the capacity to hold water gradually increases.

The saturated volumetric moisture content and residual volumetric moisture content of the improved expansive soils, and the fitting parameters of the different empirical models, as shown in Table 4.
Table 4. $\theta_s$, $\theta_r$, and correlation coefficient of fitting.

| Sample Number           | $\theta_s/%$ | $\theta_r/%$ | Correlation Coefficient $R^2$ |
|-------------------------|--------------|--------------|------------------------------|
|                         |              |              | VG_2 Model                  | VG Model       | Gardner Model   | F&X Model       |
| Unimproved expansive soil| 50.873       | 5.534        | 0.99743                     | 0.99708        | 0.99710         | 0.99777         |
| A1                      | 50.904       | 5.901        | 0.99887                     | 0.99999        | 0.99939         | 0.99999         |
| A2                      | 50.919       | 6.225        | 0.99758                     | 0.99944        | 0.99932         | 0.99957         |
| A3                      | 51.179       | 6.467        | 0.99773                     | 0.99980        | 0.99972         | 0.99972         |

From Table 4, the correlation coefficients of the four empirical models fitted above are all more than 0.99 when fitted by the models to the SWCCs of unsaturated expansive soils, indicating that the fitted results are reliable. The fitting of the various models, in descending order, is the Fredlund & Xing model, the three-parameter Van Genuchten model, the Gardner model and the two-parameter Van Genuchten model. The saturated volumetric moisture content of the expansive soil increased from 50.87% to 51.18% with an increase in the admixture of the cementation liquid at the same admixture of the bacterial liquid. Similarly, its residual volumetric moisture content increased from 5.53% to 6.47%. Furthermore, the increasing trend of both saturated and residual volumetric moisture content is non-linear. The Fredlund & Xing model with the optimum fit was selected to investigate the variation of the SWCC parameters of the improved expansive soils, to analyze the SWCC of the expansive soils under different cementation liquid content. It shows that the water-holding capacity of the improved expansive soil is gradually increasing, and the water stability of the soil, which is positively correlated with the water-holding capacity also tends to increase.

3.2. Effect of Cementation Liquid Content on SWCC of Soil Samples

The Fredlund & Xing model was chosen to analyze the test results and the parameters of the model obtained after fitting, as shown in Table 5. As a result, the SWCC of the microbially improved expansive soil can be obtained for different cementation liquid content, as shown in Figure 4.

Table 5. Fitting parameters of Fredlund & Xing model.

| Sample Number           | $\alpha$      | $n$  | $m$  | Air Entry Value |
|-------------------------|---------------|------|------|-----------------|
| Unimproved expansive soil| 896.997       | 1.356| 1.418| 226.948         |
| A1                      | 818.070       | 0.959| 1.424| 155.666         |
| A2                      | 781.332       | 0.762| 1.420| 102.804         |
| A3                      | 760.739       | 0.585| 1.462| 64.240          |

The Fredlund & Xing model assumes that the parameters $\alpha$, $n$ and $m$ are independent of each other. Where $\alpha$ is the soil parameter associated with the air entry value and can be used to characterize the value of matric suction at the inflection point of the soil-water characteristic curve [35]. As can be seen from Table 5, the air entry values for the expansive soils are 226.948, 155.666, 102.804 and 64.240 kPa from unimproved, A1 and A2 to A3 respectively. The air entry value of the improved expansive soil is significantly lower than that of the unimproved soil, and the air entry value of the improved soil tends to decrease slowly and non-linearly as the content of the cementation liquid increases. The reason for this is that there is a large amount of freedom $Ca^{2+}$ in the cementation liquid, which displaces with the $Na^+$ in the expansive soil, reducing the thickness of the electric double layer, increasing the gravitational force between the particles and effectively promoting the coalescence of the particles. At the same time, the coagulation of the soil particles results in a significant reduction in the dispersion of the soil, an increase in the agglomerates and an increase in the porous between the soil particles, which causes a reduction in the air...
entry value. On the other hand, the larger porous produced by the microbially induced carbonate precipitation, adsorbed on the contact surface between soil particles and the particle surface, effectively enhance the interparticle linkage and reduce the air entry value of the expansive soil \([36,37]\). \(n\) is positively correlated with the slope at the inflection point of the SWCC, which can be used to characterize the water-holding capacity of the soil. The lower the slope at the SWCC inflection point, the better the water holding capacity of the soil \([38]\).

As can be seen from Table 5, the values of the soil parameter \(n\) for the improved expansive soils have decreased compared to before the improvement. According to the value of \(n\), the unimproved expansive soil has the weakest water-holding capacity. The value of \(n\) in the improved expansive soil decreases gradually from A1, A2 to A3 as the content of cementation liquid in the expansive soil increases under the condition of controlling the content of bacterial liquid of 50 mL.

![Figure 4. SWCCs of expansive soils under different cementing liquid content.](image)

Figure 4 shows that the SWCC intersection of the expansive soils is located near the optimum moisture content under the conditions of the different improvement schemes. When low volumetric moisture content, the greater the content of cementation liquid, the greater the matric suction at the same volumetric moisture content. When the volumetric moisture content is higher than the moisture content at the SWCC intersection, the matric suction of the soil sample decreases with increasing the content of cementation liquid. From unimproved expansive soils to A1, A2, and A3, the SWCC of the expansive soils gradually levelled off, which means that the dehydration rate of the microbiological improved expansive soils gradually decreased, indicating that their water stability was gradually enhanced.

4. Microbial Improvement of the Microstructure of Expansive Soils

4.1. Scanning Electron Microscope Imaging

To investigate the microstructural evolution mechanism of the effect of different cementation liquid content on the soil-water characteristics of expansive soils under the same bacterial liquid content conditions. The TESCAN MIRA4 field emission scanning electron microscope was used to image and analyze the expansive soils before and after modification by the MICP method to investigate the changes in particle morphology and porous structure. The sample is an irregular sphere less than 1 cm in diameter and the sample was dried before the test. The surface of the sample is identified as the test surface, which is sprayed with gold to enhance conductivity. Secondary electron imaging was performed using a scanning electron microscope with an electron energy of 10 kev and a magnification of 5 kx.
4.2. Analysis of Test Results

Scanning electron microscope imaging tests were carried out to obtain SEM images of the expanded soil, as shown in Figure 5.

Figure 5. SEM images of expansive soil: (a) fitted curve for unimproved expansive soil; (b) A1 fitted curve; (c) A2 fitted curve; (d) A3 fitted curve.

Scanning electron microscope imaging tests were carried out to obtain SEM images of the expansive soil, as shown in Figure 5. The shape of the unimproved expansive soil particles is mainly flat and flake, the particles are mostly in edge-to-face or face-to-face contact, with large variability in pore size. The \( \text{CaCO}_3 \) crystals appeared at the contact points of the expansive soil particles after the MICP improved, and the morphology was mostly spherical particles. The contact between the particles tends to be smooth and the pore size distribution is relatively uniform. In the expansive soil improved by higher cementation liquid content, there are more \( \text{CaCO}_3 \) crystals and larger porous spaces, and the porous spaces are evenly distributed. At low levels of cementation liquid, the expansive soils contain mostly small or medium porous spaces that are uniformly distributed. Li carried out XRD analysis on the improved expansive soils, the study found that the calcite characteristic peaks increased significantly, and the main peak values were enhanced in the expansive soils treated by the MICP method [39]. The calcium carbonate precipitate produced by the test was of a different shape to the typical rhombohedral calcite. This phenomenon might be caused by the shape of the particles being obscured by the soil, or by some bacteria and fine clay particles remaining on the surface of the crystals. Based on the variation of the particle porous structure, a microscopic perspective reveals the
internal mechanism by which the air entry value of expansive soils gradually decreases with increasing contents of the cementation liquid. Compared to that of the cohesion of unimproved expansive soils, which are strongly influenced by matric suction and are more water sensitive, matric suction no longer has a restraining effect on the structure after saturation [40]. After improvement by the MICP method, the CaCO$_3$ crystals produced better cementation between the soil particles. The greater the content of the cementation liquid, the more calcium carbonate precipitation is induced and the greater the contact surface of the particles formed, which promotes the agglomeration of the soil particles, and the strength of the expansive soil is improved. Moreover, due to the low solubility of calcium carbonate, it is less affected by water, thus significantly improving the water stability of the expansive soil.

The swelling-shrinkage characteristics of expansive soils in the unsaturated state are mainly related to the water film thickness on the surface of the soil particles when they react with water. The process of water swelling in expansive soils is in essence a process whereby hydrophilic soil particles are wrapped in water molecules under the influence of electric field forces to form a water film. The thickness of the water film gradually increases as the expansive soil absorbs water, resulting in the expansion of the soil particle lattice and the swelling of the soil [41–43]. The unimproved expansive soil particles are mostly in the form of tightly packed or stacked flakes, the lattice can only expand longitudinally outwards when exposed to water. With the increase in the content of the cementation liquid, the flaky particles in the improved expansive soil gradually decrease and the pore space gradually increases. When reacting with water, the lattice of the improved soil particles expands in every direction, balancing the expansion potential in the internal space of the soil before expanding outwards, effectively reducing the expansion deformation of the expansive soil. At the same time, the microbially induced formation of calcium carbonate adheres to the surface of the expansive soil particles, reducing the interaction area between hydrophilic soil particles and water, reducing the water film thickness and interparticle spacing, tightening the soil structure and improving the strength of the soil effectively.

5. Conclusions

The SWCC of the expansive soils improved by the MICP method was obtained using the filter paper method under different conditions of cementation liquid content. Based on the theory of unsaturated soil mechanics, the experimental study and theoretical analysis were carried out on the water stability of improved expansive soils. At the same time, scanning electron microscope imaging technology was used to test on expansive soil samples. Based on the analysis of SWCC, the microscopic mechanisms affecting the water sensitivity and strength properties of the improved expansive soil were revealed. The following conclusions were obtained.

1. The content of the cementation liquid has a significant influence on the SWCC of the expansive soils improved by the MICP method. The saturated and residual water content of the improved expansive soils gradually increases with the content of cementation liquid increased. The air entry value decreases, and the water stability increases gradually.

2. Scanning electron microscope imaging tests were carried out on the expansive soils before and after improvement. The change of particle morphology and porous structure of the expansive soils under different conditions of cementation liquid content was investigated. The study shows that, compared to that of the unimproved expansive soil, the particle composition of the improved expansive soil evolves from the mutual superposition of flattened and flaky particles to spherical particles in contact with flaky particles, which increased agglomerates significantly. At the same time, with the increase in cementation liquid content, the contact between the particles tends to be smoother and the soil porous tends to be uniformly distributed gradually.

3. Based on the analysis of macroscopic and microscopic test results, it was found that the mineralization process of microorganisms changed the particle size of soil
particles and the porous structure of the soil. The microscopic mechanism affecting the water stability, swelling and shrinkage characteristics and strength properties of the improved expansive soil were revealed. After the improvement, the calcium carbonate formed by microbial induction precipitates on the surface of the soil particles and in the soil pores, enhancing the interparticle linkage, reducing the hydrophilicity and swelling-shrinkage of the soil, and improving the strength and water stability of the soil. The study also shows that the antierosion ability of the soil is improved significantly due to the increase of aggregates in the soil, the coarsening of the soil particles, and the decreasing water sensitivity of the soil.

The MICP method of improving expansive soils is effective in increasing the strength and water-holding capacity of the soil, but the ammonium ions produced during the reaction can also contaminate the soil [44,45]. The management of ammonium ions in the improvement process is an issue worthy of further study.

**Author Contributions:** Conceptualization, X.Y. and H.X.; methodology, X.Y. and H.X.; software, X.Y. and H.X.; validation, X.Y. and H.X.; formal analysis, X.Y., H.X., Z.L., J.Q., S.L. and H.S.; investigation, X.Y., H.X., Z.L., J.Q., S.L. and H.S.; resources, X.Y. and H.X.; data curation, X.Y. and H.X.; writing—original draft preparation, X.Y., H.X. and Z.L.; visualization, X.Y., H.X., Z.L., J.Q., S.L. and H.S.; supervision, X.Y., H.X. and Z.L.; project administration, H.X.; funding acquisition, H.X. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China, grant number 50978097.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Acknowledgments:** The work described in this paper was supported by a grant from the National Natural Science Foundation of China (Project No. 50978097).

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Xu, Y. Hydraulic Mechanism and Swelling Deformation Theory of Expansive Soils. *Chin. J. Geotech. Eng.* 2020, 42, 1979–1987.
2. Ye, Y.; Zou, W.; Han, Z.; Xie, P.; Zhang, J.; Xu, Y. Study on One-dimensional Swelling Characteristics of Expansive Soils Considering the Influence of Initial States. *Chin. J. Geotech. Eng.* 2021, 43, 1518–1525.
3. Ning, X.; Xiao, H.; Zhang, C.; He, B.; Xie, J. Study on the Nonlinear Creep Model of Expansive Soil. *J. Nat. Disasters* 2017, 26, 149–155.
4. Li, G.; Gong, Q.; Li, T.; Wu, J.; Chen, W.; Cao, X. Experimental Study on Properties of Weak Expansive Soil Improved by Disintegrated Sandstone. *J. Eng. Geol.* 2021, 29, 34–43.
5. Chuang, X.; Zhou, M.; Tao, G.; Zhou, R.; Peng, C.; Lin, W. Experimental Study of Dynamic Elastic Modulus and Damping Ratio of Improved Expansive Soil under Cyclic Loading by Expanded Polystyrene. *Rock Soil Mech.* 2021, 42, 2427–2436.
6. Bai, B.; Long, F.; Rao, D.; Xu, T. The effect of temperature on the seepage transport of suspended particles in a porous medium. *Hydrol. Processes* 2017, 31, 382–393. [CrossRef]
7. He, X.; Liu, H.; Han, F.; Ma, G.; Zhao, C.; Chu, Q.; Xiao, Y. Spatiotemporal Evolution of Microbial-induced Calcium Carbonate Precipitation Based on Microfluidics. *Chin. J. Geotech. Eng.* 2021, 43, 1861–1869.
8. Seung, H.C.; Hyeonyong, C.; Kyoungphil, N. Evaluation of Microbially Induced Calcite Precipitation (MICP) Methods on Different Soil Types for Wind Erosion Control. *Environ. Eng. Res.* 2021, 26, 123–128.
9. Bai, B.; Nie, Q.Z.; Wang, X.; Hu, W. Cotransport of heavy metals and SiO$_2$ particles at different temperatures by seepage. *J. Hydrol.* 2021, 597, 125771. [CrossRef]
10. Zhang, Y.; Wan, X.; Li, N.; Zhao, W.; Chen, J. Analysis of Influencing Factors and Mechanism of Microbial Clay Reinforcement. *J. China Inst. Water Resour. Hydropower Res.* 2021, 19, 246–254+261.
11. Li, X.; Wang, S.; He, B.; Shen, T. Permeability Condition of Soil Suitable for MICP Method. *Rock Soil Mech.* 2019, 40, 2956–2964.
12. Zhao, C.; Zhang, J.; Zhang, Y.; He, X.; Ma, G.; Liu, H.; Xiao, Y. Research Progress on Multi-scale Biocemented Soil. *J. Beijing Univ. Technol.* 2021, 47, 792–801.
13. Xiao, Y.; Wang, Y.; Wang, S.; Evans, T.M.; Stuedlein, A.W.; Chu, J.; Zhao, C.; Wu, H.; Liu, H. Homogeneity and Mechanical Behaviors of Sands Improved by A Temperature-controlled One-phase MICP Method. *Acta Geotech.* 2021, 2021, 1417–1427. [CrossRef]

14. Konstantinou, C.; Biscontin, G.; Jiang, N.; Soga, K. Application of Microbially Induced Carbonate Precipitation to Form Bio-cemented Artificial Sandstone. *J. Rock Mech. Geotech. Eng.* 2021, 13, 579–592. [CrossRef]

15. Bai, B.; Jiang, S.; Liu, L.; Li, X.; Wu, H. The transport of silica powders and lead ions under unsteady flow and variable injection concentrations. *Powder Technol.* 2021, 387, 22–30. [CrossRef]

16. Liu, X.; Fan, J.; Yu, J.; Gao, X. Solidification of Loess Using Microbial Induced Carbonate Precipitation. *J. Mt. Sci.* 2021, 18, 265–274. [CrossRef]

17. Safdar, M.U.; Mavroulidou, M.; Gunn, M.J.; Garelick, J.; Payne, L.; Purchase, D. Innovative Methods of Ground Improvement for Railway Embankment Peat Fens Foundation Soil. *Géotechnique* 2021, 71, 985–998. [CrossRef]

18. Gowthaman, S.; Chen, M.; Nakashima, K.; Kawasaki, S.; Frontriers, M. Effect of Scallop Powder Addition on MICP Treatment of Amorphous Peat. *Front. Environ. Sci.* 2021, 9, 690376. [CrossRef]

19. Jiang, W.; Zhang, C.; Xiao, H.; Luo, S.; Li, Z.; Li, X. Preliminary Study on Microbially Modified Expansive Soil of Embankment. *Geomech. Eng.* 2021, 26, 301–310.

20. Li, X.; Zhang, C.; Xiao, H.; Jiang, W.; Qian, J.; Li, Z. Reducing Compressibility of the Expansive Soil by Microbiological-Induced Calcium Carbonate Precipitation. *Adv. Civ. Eng.* 2021, 2021, 1–12. [CrossRef]

21. Tiwari, N.; Satyam, N.; Sharma, M. Micro-mechanical Performance Evaluation of Expansive Soil Biotreated with Indigenous Bacteria Using MICP Method. *Sci. Rep.* 2021, 29, 1–12. [CrossRef]

22. Abdelbaki, A.M. Assessing the Best Performing Pedotransfer Functions for Predicting the Soil-water Characteristic Curve According to Soil Texture Classes and Matric Potentials. *Eur. J. Soil Sci.* 2021, 72, 154–173. [CrossRef]

23. Bai, B.; Xu, T.; Nie, Q.; Li, P. Temperature-driven migration of heavy metal Pb²⁺ along with moisture movement in unsaturated soils. *Int. J. Heat Mass Transf.* 2020, 153, 119573. [CrossRef]

24. Bai, B.; Rao, D.; Chang, T.; Guo, Z. A nonlinear attachment-detachment model with adsorption hysteresis for suspension-colloidal transport in porous media. *J. Hydrol.* 2019, 578, 124080. [CrossRef]

25. Zhang, G.; Wang, L.; Cao, Z.; Li, Q. Comparative Study of Different Methods for Determining the Soil Water Characteristic Curve Model Considering Uncertainty. *J. Nat. Disasters* 2018, 27, 151–158. [CrossRef]

26. Fredlund, D.G. State of Practice for Use of the Soil-Water Characteristic Curve (SWCC) in Geotechnical Engineering. *Can. Geotech. J.* 2019, 56, 1059–1069. [CrossRef]

27. Sarda, D.; Choonia, H.S.; Sarode, D.D.; Lele, S.S. Biocalcification by *Bsacillus pasteurii* Urease: A Novel Application. *J. Ind. Microbiol. Biotechnol.* 2009, 36, 1111–1115. [CrossRef]

28. Pei, D.; Liu, Z.; Hu, B.; Wu, W. Progress on Mineralization Mechanism and Application Research of *Sporosarcina pasteurii*. *Prog. Biochem. Biophys.* 2020, 47, 467–482.

29. Bai, F.; Liu, S.; Yuan, J. Measurement of SWCC of Nanyang Expansive Soil Using the Filter Paper Method. *Chin. J. Geotech. Eng.* 2011, 33, 928–933.

30. Zhang, H.; Zhang, F.; Yuan, M. Study of Temperature Effect on Domestic Quantitative Filter Paper’s Calibration Curves. *Rock Soil Mech.* 2016, 37, 274–280.

31. van Genuchten, M.T. A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Sci. Soc. Am. J.* 1980, 44, 892–898. [CrossRef]

32. Pan, D.; Ni, W.; Yuan, K.; Zhang, Z.; Wang, X. Determination of Soil-water Characteristic Curve Variables Based on VG Model. *J. Eng. Geol.* 2020, 28, 69–76.

33. Gardner, W.R. Some Steady-state Solutions of the Unsaturated Moisture Flow Equation with Application to Evaporation from A Water Table. *Soil Sci.* 1958, 85, 228–232. [CrossRef]

34. Fredlund, D.; Xing, A. Equations for the Soil-water Characteristic Curve. *Can. Geotech. J.* 1994, 31, 521–532. [CrossRef]

35. Zhou, B.; Kong, L.; Chen, W.; Bai, H.; Li, X. Analysis of Characteristic Parameters of Soil-water Characteristic Curve (SWCC) and Unsaturated Shear Strength Prediction of Jingmen Expansive Soil. *Chin. J. Rock Mech. Eng.* 2010, 29, 1052–1059.

36. Li, C.; Shi, G.; Wu, H.; Wang, C.; Gao, Y. Experimental Study on Bio-mineralization for Dispersed Soil Improvement Based on Enzyme Induced Calcite Precipitate Technology. *Rock Soil Mech.* 2021, 42, 333–342.

37. Wang, Z.; Zhang, N.; Cai, G.; Jin, Y.; Ding, N.; Shen, D. Review of Ground Improvement Using Microbial Induced Carbonate Precipitation (MICP). *Mar. Georesour. Geotechnol.* 2017, 35, 1135–1146. [CrossRef]

38. Wang, X.; Xu, C.; Wang, S.; Li, X. Study on Overburden Pressure Effect of Expansive Soil-water Characteristic Curve. *Chin. J. Rock Mech. Eng.* 2020, 39, 3067–3075.

39. Li, X. Study on Microstructure and Mechanical Properties of Expansive Soil Improved by MICP Technology. Ph.D. Thesis, Central South University of Forestry and Technology, Changsha, China.

40. Yao, H.; Liu, S.; Cheng, C. Scopic Essence of Cohesion of a Natural Cemented Soil. *Chin. J. Rock Mech. Eng.* 2001, 20, 871–874.

41. Leng, T.; Tang, C.; Xu, D.; Li, Y.; Zhang, Y.; Wang, K.; Shi, B. Advance on the Engineering Geological Characteristics of Expansive Soil. *J. Eng. Geol.* 2018, 26, 112–128.

42. Bai, B.; Nie, Q.; Wu, H.; Hou, J. The attachment-detachment mechanism of ionic/nanoscale/microscale substances on quartz sand in water. *Powder Technol.* 2021, 394, 1158–1168. [CrossRef]
43. Tan, L. The Effect of Lattice Expansion and Contraction of Montmorillonite on its Volume Change. Hydrogeol. Eng. Geol. 1981, 06, 5–7+38.
44. Keykha, H.A.; Mohamadzadeh, H.; Asadi, A.; Kawasaki, S. Ammonium-Free Carbonate-Producing Bacteria as an Ecofriendly Soil Biostabilizer. Geotech. Test. J. 2019, 42, 19–29. [CrossRef]
45. Mohsenzadeh, A.; Aflaki, E.; Gowthaman, S.; Kawasaki, S.; Ebadi, T. A two-stage treatment process for the management of produced ammonium by-products in ureolytic bio-cementation process. Int. J. Environ. Sci. Technol. 2021, 9, 18313. [CrossRef]