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Preliminary study on microbially modified expansive soil of embankment

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Abstract. The improvement of expansive soils has crucial academic research significance and engineering application value. The regular practice using chemical improvement methods may be helpful to improve the expansive soil; however, at the cost of inconvenient material acquisition, troublesome mixing methods, expensive construction, and polluting the soil environment. To this end, based on the microbial induced calcium carbonate precipitation (MICP) technology, we carry out a series of soil modification tests on the expansive soil for the roadbed filling in Nanning, Guangxi. Considering the problematic behaviors of the expansive soil and its significant adverse effect on engineering, this paper focuses on the soil improvement; particularly, we aim to study the improved soil's physical properties, limit moisture content and swelling and shrinkage rates under the action of dry and wet cycles. It is found that the swelling index of the improved expansive soil has been decreased significantly, the free expansion rate drops to 14.9%, such that the samples fall into the category of non-expansive soil. The liquid limit and plastic limit of soil samples decreased to 47.2% and 20.4%, respectively, after 6 times of microbial treatment. Moreover, after several high-pressure consolidation tests under dry-wet cycle conditions, the hydrophilic capacity of the improved expansive soil is significantly weakened, and its corresponding water absorption induced swelling rate and drainage-induced shrinkage rate are significantly reduced. The above research results show that it is feasible to use the MICP technology to improve the swelling and shrinkage characteristics of the expansive soil; in particular, after six treatments with the microbial solution, all indices of the expansive soil achieve the best improvement effect.

Keywords: dry and wet cycles; fill expansive soil; MICP; swelling and shrinkage indices

1. Introduction

Expansive soil is a multi-fissure, expansive and catastrophic soil formed in the natural geological process. Since it is mainly composed of three hydrophilic clay minerals, such as kaolinite, montmorillonite, and illite, it is easy to swell by absorbing water and shrink by drying. As a consequent, expansive soil often causes engineering problems, and improper treatment may cause a series of engineering accidents or geohazards, e.g., excessive expansion of the soil during the rainy season causes uneven deformation, bulging and even cracking of the pavement, and it also causes cracks in the walls of light buildings on the expanded soil, causing house damage (Akcin 2021). Besides, under the environmental effects of the wet and dry cycle, the depth of crack development has become a critical issue affecting the stability of expansive soil slopes and engineering governance (Shi *et al.* 2014, Lu and Liu 2017). Therefore, how to effectively improve the swelling and shrinkage of excavated expansive soil when building roads or railways in expansive soil areas has become the most critical issue in engineering construction.

The general method of replacing expansive soil is neither economical nor environmental, as the disposed soil may occupy the land and cause environmental pollution (Soltani *et al.* 2019). Therefore, the conventional method is to use chemical and physical improvement methods to reduce the swelling and shrinkage rate and axial strain of the expansive soil, to meet the requirements of the relevant specifications for the expansive soil as a roadbed filling material.

At present, there are more sophisticated methods for improving the swelling of expansive soil at home and abroad, which are mainly chemically modified by adding a certain amount of inorganic materials such as Cationic-electrokinetic, cement, HTAB, fly ash and lime (Abdullah and Al-Abadi 2010, Shang and Geng 2010, Um Shankar and Phanikumar 2015, Saride *et al.* 2013, Stdtz *et al.* 2012). Scholars at home and abroad have carried out extensive research on the swelling and shrinkage characteristics of expansive soils modified with various admixtures under the action of dry and wet cycles (Puppala *et al.* 2013, Rao and Rao 2010, Wang and Wei 2014). Studies have shown that these admixtures can effectively improve the swelling and shrinkage of the expansive soil, as well as the axial strain, and increase its strength. However, these improved methods for filling expansive soils all have certain shortcomings; either the mixing method is troublesome, and the environment is much polluted, or the materials are

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Table 1 Physical properties of the expansive soil

Soil source	Natural density (g/cm^2)	Max dry density (g/cm^2)	Relative gravity G_s	Liquid limit /%	Plastic limit /%	Plastic index /%	Optimum moisture content /%	Free swelling rate /%
Nanning	1.88	1.94	2.70	60.8	22.4	38.4	16.2	61.3

Table 2 Chemical composition of the expansive soil

Si^{4+}/%	Al^{3+}/%	Fe^{3+}/%	K^{+}/%	Mg^{2+}/%	Ca^{2+}/%	Ti^{4+}/%	Cu^{2+}/%	S^{2+}/%	Mn^{2+}/%
23.5	57.6	8.9	4.2	2.3	1.6	0.9	0.7	0.2	0.1

inconvenient and expensive to manufacture (Yang *et al.* 2013). In addition, there are some reinforcement methods (Abbey *et al.* 2020, Sja *et al.* 2021, Abbey *et al.* 2019) for other special soils, but these improved methods are not suitable for expansive soils, nor are they suitable for engineering practice. Therefore, it is necessary to explore new material, process and method for improving the filling of expansive soil.

In recent years, with the development of microbial geotechnical engineering technology, the research on the use of microbial technology, e.g., the microbial induced calcium carbonate precipitation (MICP), to improve soft soil environment has made wide application (Dawoud *et al.* 2014, Osinubi *et al.* 2020). MICP technology mainly uses urease produced by the metabolism of microbes (bacillus) to hydrolyse urea to produce carbonate ions, and then reacts with calcium ions in the soil to produce calcium carbonate colloidal precipitation. This calcium carbonate colloid precipitates on the surface of soil particles and forms calcium carbonate crystals after curing. The loose soil particles are then connected and to fill the voids in the soil, so that the voids between the soil particles reduce. Moreover, soil resisting capacity may be improved as the bonding between the soil particles is enhanced, forming a more firm and impermeable structure. Notably, unlike the conventional chemical soil treatment, the microbes are easy to cultivate without causing soil pollution or any other environmental issues, and may effectively reduce the cost of engineering (Feng and Montoya 2017). Therefore, the MICP is expected to become a new, efficient, economical and environmentally friendly method for improving various soft soils.

The use of MICP technology to solidify sand has achieved good performances at home and abroad (Liang *et al.* 2015, Do *et al.* 2019, Cheng *et al.* 2012, Imran *et al.* 2019). For example, the application of MICP in deserts, coastal slopes and marine soft soils has been preliminarily studied (Qureshi *et al.* 2017, Salifu *et al.* 2015, Kwon *et al.* 2019), and detailed experimental studies on the MICP modified sandy soil were conducted through resonance tests, undrained shear tests, and SEM methods (Im *et al.* 2017, Dejong *et al.* 2006, Li *et al.* 2017). Also, preliminary studies have been carried out on the application of MICP technology to improve organic clay (Yasodian *et al.* 2012, Peng *et al.* 2019, Sidik *et al.* 2014), tropical residual soil (Soon *et al.* 2013), soil pollution (Achal *et al.* 2011), and soil crack repair (Liu *et al.* 2020, Stefani *et al.* 2020), all of which have achieved staged research results to varying degrees. Nevertheless, there are few reports on the application of MICP technology to improve the expansive soil for embankment filling.

This paper, therefore, aims to investigate the MICP performance in improving the expansive soil. Section 2 begins with the introduction of the soil samples, their properties and the preparation of the microbial solution. This is followed by the presentation of the relevant soil tests to investigate the influence of the microbial solution on the expansive soil samples. After that, a series of test results of swelling and shrinkage rates, axial deformation, and the effect of dry-wet cycles are shown and analysed in Section 4. Finally, some conclusions are drawn in Section 5.

2. Soil samples and properties

2.1 Physical properties of the expansive soil

The expansive soil samples used in the test were collected from the road engineering in Nanning, Guangxi, and are mainly composed of the highly hydrophilic clay minerals montmorillonite, illite and kaolinite. The soil is scaly, mainly yellowish and off-white, and feels sandy and gritty. According to the Standard for Geotechnical Test Methods (GBT50123-2019), it is determined to be a medium expansive soil through the expansibility test. The physical properties of soil samples have been tested to obtain basic physical properties and chemical composition. The test results are shown in Tables 1 and 2, respectively.

2.2 Preparation of microbes

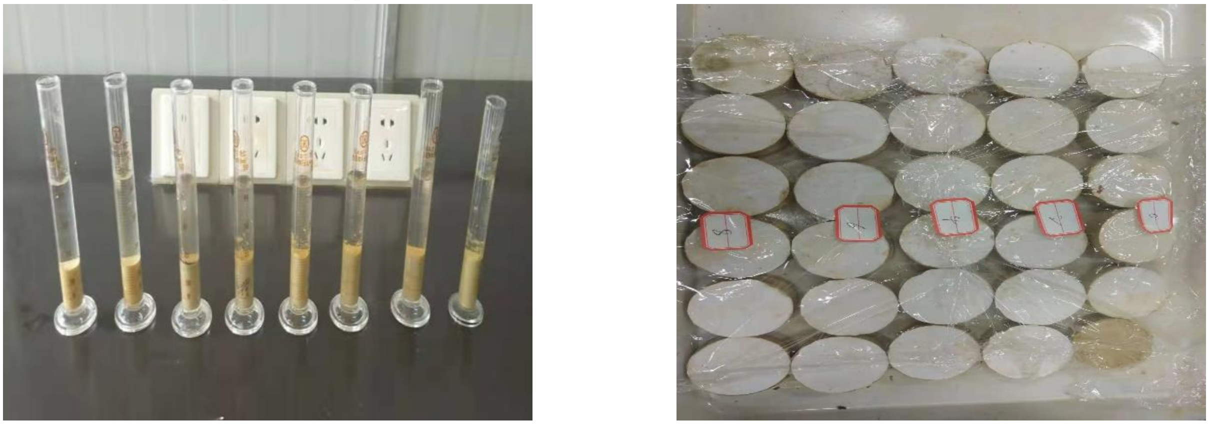
The microbes used in the experiment were derived from Bacillus bacillus (No. ATCC11859) cultivated by the China General Microbes Collection Management Center (CGMCC). This bacterium is selected from the natural soil environment and has no adverse effects on the human and biological environment, and its ability to produce urease is superior. It has been widely used in the study of MICP technology. Before activation of Sporosarcina (formerly known as Bacillus pasteurii), it is a white lyophilised powder encapsulated in ampoules. When the first activation is performed, the dry powder is completely dissolved with 0.1-0.2ml of sterile water and inoculated on two inclined surfaces due to insufficient inoculation volume; otherwise, the lyophilised powder that is in the dormant state might be unsuccessful in recovering if the powder is inoculated on many surfaces. Immediately after the inoculation, the slanted surface was placed in an SPX-250B-Z biochemical

Table 3 Treatment plan of the soil samples

Process	Grouting times	Compaction/%	Mole ratio of urea to calcium chloride	Cement concentration /M
Times of microbial treatment	0，2，4，6，8	95	1：1	1.0

(a) Inoculate with sporosarcina pasteurii (b) Activate sporosarcina pasteurii

(c) Culture sporosarcina pasteurii (d) Mix the soil with the microbial solution



(e) Free swelling tests (f) Soil samples for dry-wet cycling tests

Fig. 1 Preparation of microbial solution and soil samples

incubator and cultured at a constant temperature of 30°C for 18-24 h. In order to ensure the activity of the microbes, it is best to re-attach the slope surface of the first inoculation to two new slopes for secondary culture. The cultivated surface was inoculated into the liquid medium again for experimental cultivation.

The culture medium components required for the bacteria are urea (CASO AGAR +) 20 g/L, casein peptone (Casein Peptone) 15 g/L, soya peptone (Soya Peptone) 5 g/L, sodium chloride (NaCl) 5 g/L, distilled water (H_2O) 1L and 0.2 mol/L sodium hydroxide (NaOH) solution (to adjust the pH of the liquid culture medium, pH = 7.3). Use a vertical pressure steam steriliser to sterilise the Erlenmeyer flask containing 162 ml of culture medium for 30 minutes at high temperature and high pressure (120 degrees Celsius,1.4 MPa), and take it out after cooling under reduced pressure. After the water on the outside of the Erlenmeyer flask evaporates, move the Erlenmeyer flask to be inoculated to the SW-CJ-F single-person double-sided purification workbench with the inoculation ring for 20 minutes for UV sterilisation. The activated microbes are inoculated into the culture medium, sealed with a sealing film, and then transferred to an intelligent precision shaker with a rotation speed of 150r/min. After culturing at a constant temperature of 30°C for about 48 hours, a turbid bacterial solution was formed, and the concentration of the microbe solution was measured by a spectrophotometer. When the absorbance OD_{600} is about 1, it can be considered that the concentration of the bacterial solution reaches the test requirements. The remaining microbes were stored in a refrigerator at 4 degrees Celsius, ready for regular activation to maintain their activity for future use.

2.3 $CaCl_2$ solution preparation

The main role of the calcium chloride solution is to provide sufficient calcium ions for the MICP process. In the test, the concentration of $CaCl_2$ solution was 0.2mol / L, and the formula was: 1000ml of distilled water and 43.8g of $CaCl_2 \cdot 6H_2O$ crystals.

3. Test scheme of soil samples

To investigate the soil's free, unloaded and loaded swelling rates after the microbial improvement, and the swelling-shrinking deformation under the dry and wet cycling processes, it is necessary to ensure that the test soil is in a solid state (rather than a liquid one), thus the microbial solution can be fully utilised to improve the soil. When using MICP technology to improve the expansive soil, two problems need to be well controlled. On the one hand, the concentration of the bacterial solution must be well controlled with the OD600 absorbance of around 1. On the other hand, the moisture content of the soil must be controlled, as unlike the sandy soil, the cohesive soil cannot be treated by immersing the soil sample in the microbial solution (Liu *et al.* 2019); otherwise, the moisture content of the soil sample is too large to form a test soil sample. Therefore, the amount of microbial solution should be controlled according to the optimal moisture content required for the soil to reach the maximum compaction. To solve the above problems, the soil sample may be either treated multiple times or treated once only but with a concentrated microbial solution (Liu *et al.* 2019). We adopted the multiple-time treatment in our tests, and the amount of microbial solution is controlled based on the optimal moisture content of the soil compaction, that is, $Wo = Wp \pm 2\%$. The test treatment scheme is shown in Table 3.

The test soil preparation process is as follows:

1) Strictly prepare a certain amount of microbial solution according to the microorganism preparation method; 2) measure the absorbance of the microbial solution with a spectrophotometer to ensure that the concentration of the microbial solution after the culture meets the test requirements; 3) prepare the microbial solution with absorbance OD_{600} of about 1, and obtain the optimal moisture content (16.2% through testing) required for the expansive soil to reach the maximum compaction. This is followed by the preparation of the expansive soil sample: firstly, a certain proportion of the $CaCl_2$ solution was air-dried in a soil sample; then, the prepared microbial solution (based on optimum moisture content) was sprayed into the expansive soil. To ensure the full and uniform mixture, the treated soil sample is mixed layer by layer, so that the expansive soil could adequately react with the urease hydrolysate in the metabolite of sporosarcina pasteurii to complete the MICP cementation process. Finally, air-dry and crush the treated soil samples under natural conditions; 4) repeat the process of 3), respectively, for twice, four, six and eight times to complete the MICP cementation process; 5) place the air-dried soil samples that meet the requirements on a rubber plate, crush them with a wooden stick, pass through a 2mm sieve, and then take enough soil to prepare five samples of different numbers of microbial treatment for the testing purposes; 6) the soil samples are prepared by the static pressure method according to the "Highway Geotechnical Test Regulations" (JTG E40-2019). The microbe culture and soil sample preparation are shown in Figs. 2 (a) to 2 (f), respectively.

4. Test results and analysis

4.1 Swelling test

According to the T0124-1993, T0125-1993, and T0126-1993 of the Highway Geotechnical Test Code (JTG E40-2019), the tests of free swelling, unloaded and 100kPa loaded swelling rates were conducted. The test results are shown in Table 4.

From Table 4, it can be found that the effect of reducing the swelling characteristics of the expansive soil by microbially induced calcium carbonate precipitation is evident. With the increase of the number of microbial suspension treatments, the free swelling, unloaded and loaded swelling rates of the improved expansive soil began to decrease rapidly. Data fitting analysis of the three swelling rates in Table 4 obtains the variation curves of various swelling indices with the number of treatments, as shown in Fig. 2.

Figure 2 further shows the quantitative relationship between changes in these swelling indicators and the number of microbial treatments. For example, for free swelling, unloaded and loaded swelling rates, the soil samples that have not been treated with microbial bacterial solution are 61.3%, 14.2%, and 1.8%, respectively; while

Table 4 Test results of swelling indices after the treatment of MICP

Swelling index	Times of microbial treatment				
	0	2	4	6	8
Free swelling rate	61.3	48	22	14.9	15.2
Unloaded swelling rate	14.2	6.7	4.2	2.80	2.82
100kPa loaded swelling rate	1.8	1.15	0.72	0.4	0.6

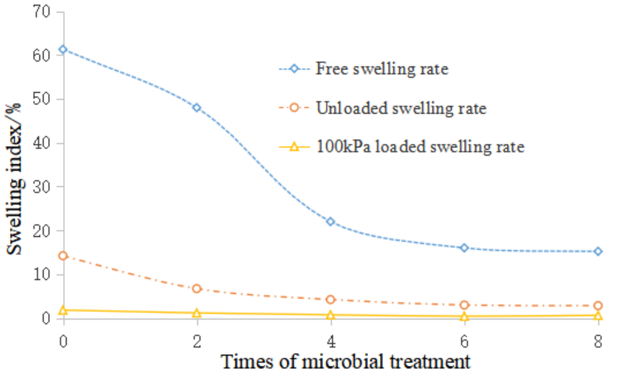


Fig. 2 Relationship between swelling index and number of microbial treatments by microbes

these swelling indices significantly decreased to 14.9%, 2.80% and 0.4%, respectively, for the microbial solution treated soil samples. That is to say, after six times of microbial solution treatment, the three swelling indices of the expansive soil sample have decreased significantly, the decline is up to 75.69%, 80.28%, and 77.78%, respectively. As a result, the soil samples after this treatment no longer have the characteristics of expansive soil but have been transformed into non-expansive soil.

Table 4 and Fig. 2 also show that when the number of microbial solution treatments is increased from 6 to 8, the three swelling rates increase slightly, although the increase is small. This phenomenon was first identified in our study, so there are no any relevant explanations yet. Based on our sampling process, we proposed the following consideration: when the number of treatments exceeds a certain amount, the soil sample is compacted many times during the treatment process, and some of the soil particles are compacted even more finely. More fine particles mean that more calcium carbonate colloids are needed for cementation. When some of the fine particles are not cemented by calcium carbonate precipitation, the swelling performance of the soil will increase. This is indeed an exciting finding that needs further in-depth analysis in the future.

Therefore, it is advisable to treat the suspension 6 times as the cut-off point, such that when the number of microbial treatments is 6 times, the swelling characteristics of the expansive soil are best improved. This indicates when using MICP technology to improve the expansive soil, on the one hand, it is necessary to achieve a specific concentration of microbial bacteria liquid; on the other hand, to achieve the best effect of the expansive soil improvement, there is an optimal number of microbial treatments. This is because increasing the number of treatments (before reaching the optimum treatment) generate more calcium carbonate colloids that can be precipitated in the microbial solution, such that the more expansive soil particles will be cemented, leading to lower swelling indices. However, when the number of treatments exceeds a certain amount, the particles of the expanded soil will become finer as too many treatment times cause damage to the previously formed calcium carbonate crystals around the clay particles, exposing some particles to contact with water, resulting in additional swelling effect.

Therefore, it is suggested not to pulverise the expansive soil during the microbial processing excessively.

Table 5 Tested results of limit water content after improved

Physical properties	Times of microbial treatment				
	0	2	4	6	8
Liquid limit /%	60.8	56.7	52.9	47.2	50.6
Plastic limit /%	22.4	21.6	20.2	20.4	21.3
Plastic index	38.4	35.1	32.7	26.8	29.3

4.2 Limit moisture content test

According to T0118-2019 in Highway Geotechnical Test Regulations (JTG E40-2019), Atterberg limits test of the microbially modified expansive soil were carried out. The test results are shown in Table 5.

From Table 5, similar to the reduction of the swelling indices with the treatment times, both the liquid limit and plastic limit of the expansive soil decrease as the number of microbial treatments increases from 2 to 6. For example, after six treatments with the microbial suspension, at the optimal initial water content of 16.2%, the liquid limit of the soil decreased by 22.37% to 47.2% that is less than 50%, a significant reduction by comparing with the untreated expansive soil. Also, the plastic limit decreased by 8.93%.

As a result, the plasticity index is decreased to 26.8%, close to 26%; the decrease was 30.21%. Based on the indices liquid limit ≤ 50% and plastic index ≈ 26, it can be concluded that the expansive soil before the MICP treatment belongs to a high liquid limit soil while the soil after the treatment is no longer the high liquid limit soil.

4.3 Swelling and shrinking tests under cyclic wet and dry conditions

4.3.1 Test method

30 soil samples with the diameter of 61.8mm and the height of 20mm were prepared from the MICP treated expansive soil that has been treated 0, 2, 4, 6, and 8 times according to the initial moisture content of 16.2%. The soil samples were placed in a GDG-4S triple high-pressure consolidation instrument, where a vertical pressure of 12.5 kPa was applied.

These samples were subject to cyclic swelling-shrinking test as follows: 1) the tested sample in the consolidation instrument was first dried in an environment of 25 degrees Celsius for 24 hours, so the water is allowed to dry naturally; 2) then immerse the soil samples in the consolidation instrument for 24 hours, where the water channel is filled with water; 3) during the drying and wetting, the axial deformation of the soil samples are recorded for 24h; 4) after the sample deformation is stable, drain the water in the consolidation instrument. The above 4 processes consist of a complete wet and dry cycle. Repeat the same process for 6 times.

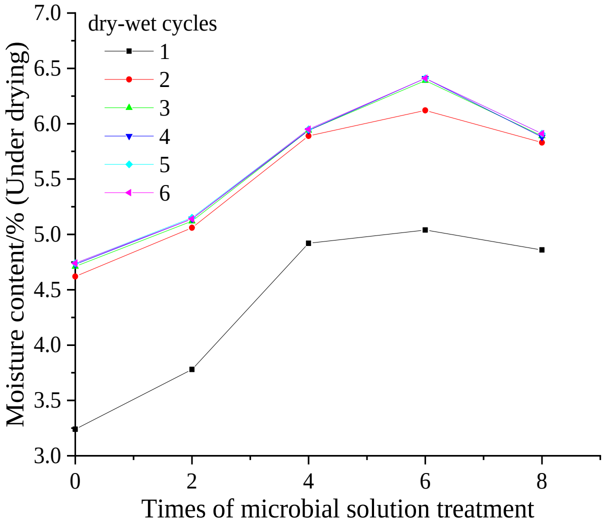


Fig. 3 The influence of dry-wet cycle on drying moisture content

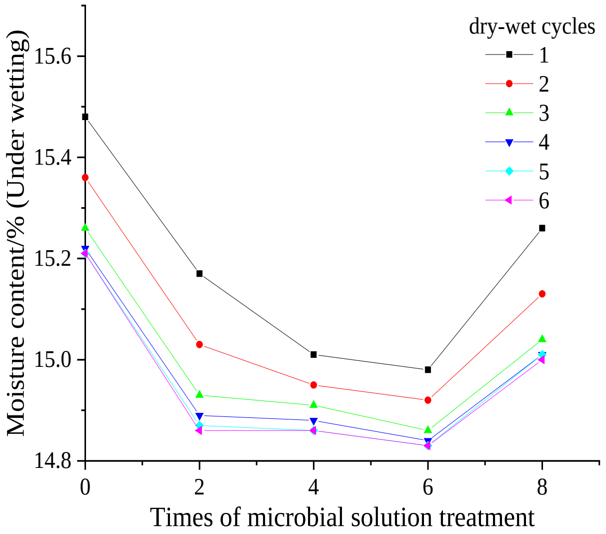


Fig. 4 The influence of dry-wet cycle on the wetting moisture content

Table 6 Effect of dry and wet circles on axial deformation

Times of dry-wet cycles	Times of microbial treatment	Axial deformation /%	
		Under drying	Under wetting
1	0	-5.62	10.23
	2	-4.73	8.67
	4	-3.92	6.88
	6	-3.39	5.49
	8	-3.61	5.85
2	0	-5.21	9.73
	2	-4.36	7.97
	4	-3.62	6.39
	6	-3.08	5.18
	8	-3.34	5.54
3	0	-4.75	9.32
	2	-4.18	7.54
	4	-3.45	5.88
	6	-2.79	4.97
	8	-3.27	5.33
4	0	-4.47	9.09
	2	-3.93	7.23
	4	-3.29	5.45
	6	-2.53	4.64
	8	-3.18	4.98
5	0	-4.37	8.93
	2	-3.67	7.12
	4	-3.12	5.34
	6	-2.34	4.57
	8	-3.06	4.89
6	0	-4.36	8.92
	2	-3.66	7.11
	4	-3.11	5.32
	6	-2.34	4.57
	8	-3.05	4.88

4.3.2 Effect of dry-wet cycles on the moisture content of improved expansive soil

The initial moisture content of all expansive soil samples was set to 16.2%. The test was carried out according to the method of multiple dry-wet cycles. It is found that the moisture content of the microbially modified expansive soil samples changed with the number of dry-wet cycles, as shown in Figs. 3 and 4.

From Figs. 3 and 4, it can be found that, compared with the untreated expansive soil sample, the drying-induced moisture contents (25˚C, 24hrs) of the expansive soil samples after 2, 4, 6, and 8 treatments by the microbial treatment were increased, while the wetting-induced moisture content (25˚C, 24hrs) was generally decreased. From the microstructure changes observed by scanning electron microscope (in section 4.4), the formed calcium carbonate envelops the clay mineral particles (after water absorption), making it difficult for the water to be discharged under drying. Similarly, when wetting, the water is also difficult to be absorbed by the enveloped clay minerals, resulting in lower water contents. Among all the changes in moisture contents, it is found that the most drastic change occurred after the first two dry-wet cycles, while fewer changes were observed after that. It can also be found from Figs. 4 and 5 that the drying-induced and wetting-induced moisture contents of the expansive soil samples have reached the smallest changes after being treated with the microbial solution for six times. This once again indicates that the optimal number of times of microbial solution treatment is six times.

Also, after 24 hours of the first drying, the moisture content of the untreated expansive soil samples decreased from 16.2% to 3.24% with a decrease of 80%. The 3.24% moisture content was then increased to 15.48% after being wet for 24 hours, decreased by 4.44% compared with the original 16.2% moisture content. As a comparison, after 6 times of microbial treatment, the corresponding drying-induced and wetting-induced moisture contents of the expansive soil samples were reduced to 5.04% and 14.98%, respectively, which were 68.9% and 7.53% lower than the initial moisture content. Such reductions show that as long as the samples treated with the microbial bacterial solution, the drying-induced and wetting-induced moisture contents would be changed significantly. In other words, the hydropathic capacity of the expansive soil after the microbial treatment with MICP technology is significantly weakened. The reason is that, after several times of microbial solution treatment, the microbes induce the precipitation of calcium carbonate that may partially or entirely encapsulate the hydrophilic mineral particles in the expansive soil, as later shown in SEM observation in Section 4.4.

4.3.3 Effect of dry-wet cycles on the axial strain of improved expansive soil

After the samples have been subjected to multiple wet and dry cycles, the changes in the axial deformations of drainage-induced shrinkage and immersion-induced swelling are shown in Table 6, where the positive deformations are for soil swelling while the negative for soil shrinkage.

It can be found from Table 6 that with the increase of the number of drying and wetting cycles, the axial deformation of the expansive soil samples has changed differently. For example, after the first dry-wet cycle, its axial deformation was the largest, while after the fifth dry-wet cycle, its axial deformation gradually stabilised. Compared with the untreated expansive soil sample, the axial deformations of the expansive soil sample treated with the microbial bacterial solution were significantly reduced when either immersed in water to expand or drained water to shrink. It was also found that the axial deformation of the expansive soil samples reached the minimum after 6 times of microbial treatment. This again confirms that the microbes induce the precipitation of calcium carbonate colloid to wrap the expansive soil particles and fill the pores in the soil, resulting in the solidification of the expansive soil.

4.3.4 Variation of swelling rates with dry-wet cycle and microbial treatment times

Under different dry and wet cycles, the swelling rates of the expansive soil samples change with the number of microbial treatments, as shown in Fig. 5. It shows that the swelling rates of the expansive soil samples are consistent with the number the microbial treatment under various dry and wet cycles, i.e., the swelling rate of the sample first decreased linearly before the sixth treatment, at which the rates reached the minimum; then the rates increased slightly.

Under the same number of microbial solution treatment, the swelling rate of the expansive soil samples reached the maximum reduction after the first wet-dry cycle, while the reduction of the swelling rate considerably decreased after the 2nd and 3rd dry-wet cycles, compared to the reduction of the first cycle. Nevertheless, this slight rate reduction continues till the completion of the 6th dry-wet cycle to achieve the minimum swelling rate, and the swelling rates of all samples stabilised, without further reduction.

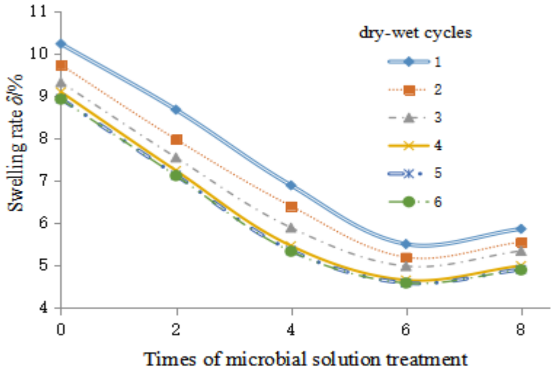


Fig. 5 Variation of swelling rates with microbial treatment times under various dry-wet cycles

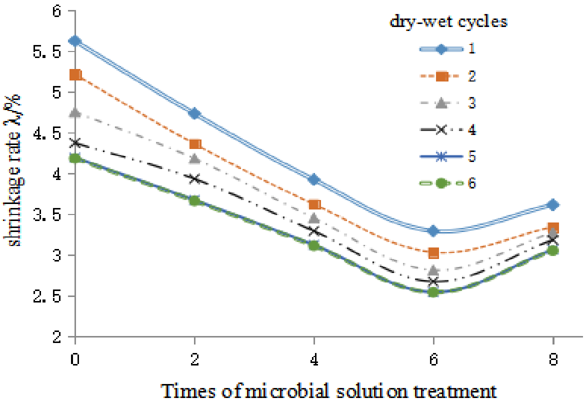


Fig. 6 Variation of shrinkage rates with microbial treatment times under various dry-wet cycles

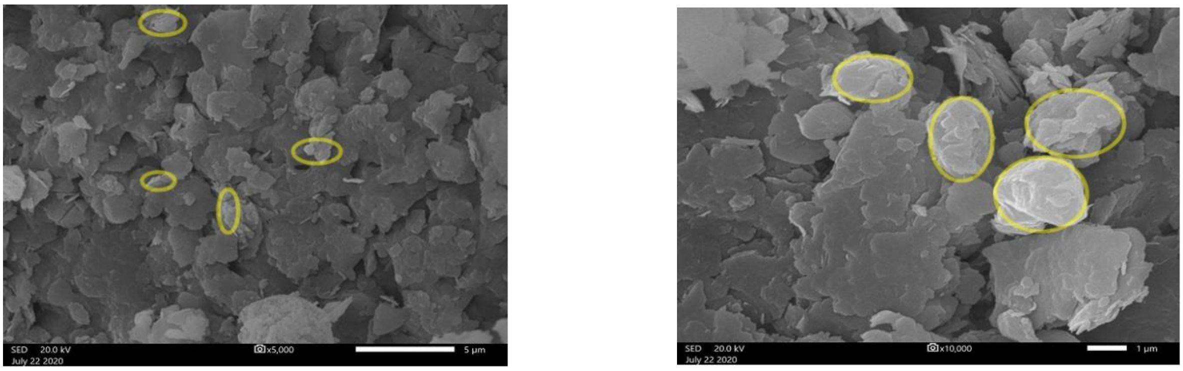
Therefore, compared with the untreated expansive soil, the treated soil’s swelling rate has been significantly improved (reduced) after 6 times of the microbial treatment; for instance, the treated soil’s swelling rate was decreased by 48.95% after 4 dry-wet cycles.

4.3.5 Variation of shrinkage rates with dry-wet cycle and microbial treatment times

The changes in the shrinkage of the expansive soil samples with the number of times of microbial solution treatment under different wet and dry cycles are shown in Fig. 6.

It can be seen from Fig. 5 that under different numbers of dry and wet cycles, the variation of the shrinkage rates of the expansive soil samples subjected to various microbial treatments followed the similar pattern. That is, the shrinkage rate initially decreased linearly from the first to sixth microbial treatment, then the rate rose slightly at the 8th treatment.

Comparing Fig. 5and Fig. 6, it can be found that under different dry-wet cycles, the swelling and shrinkage rates of the expansive soil samples are similar to the changes in the number of microbial treatments. Under the same number of microbial solution treatment, the shrinkage rate of the expansive soil samples reached the maximum after the first wet and dry cycle. After that, the shrinkage rates after the 2nd, 3rd and 4th dry-wet cycles were reduced much less



(a) Soil sample before improvement (b) Soil sample after improvement

Fig. 7 Scanning electron microscope pictures before and after improvement (courtesy from Li *et al.* 2021)

than the reduction in the first treatment. A closer look shows that after the fifth dry-wet cycle, the shrinkage of the sample stabilised until the sixth treatment to achieve the minimum shrinkage rates under various dry-wet cycles. This confirms the significant role of the microbes-induced calcium carbonate precipitation in improving (reducing) the expansive soil's swelling and shrinkage capability. As a result of the 6 times microbial treatments, the soil's shrinkage rate after 5 dry-wet cycles was decreased by 46.5% compared with the untreated expansive soil.

4.4 Scanning electron microscope test

In order to explore the influence of MICP on the microstructure of soil samples, scanning electron microscopy was used to observe the soil samples before (Fig. 7(a)) and after (Fig. 7(b)) the improvement. Note that in Fig. 7(b), it shows a typical sample treated after 6 times but without experiencing the dry-wet cycle.

From Fig. 7(a), the morphology of the soil-like crystals before the improvement is mostly irregular particles, the soil particles have gaps, and there are only a little bit of natural calcium carbonate crystal molecules on tips of some soil particles. While in Fig. 7(b), in the soil sample modified by MICP technology, a large number of calcium carbonate crystals were generated around the hydrophilic mineral particles. As a consequence, the hydrophilic ability and swelling characteristics of the expansive soil are significantly reduced. These calcium carbonate crystals also fill the pores among the soil particles, which is beneficial to prevent the loss of bound water.

5. Conclusions

Expansive soil improvement has been a hot research topic in academia and engineering. However, currently the most widely used chemical improvement method has many defects, including cost, material selection, mixing, and environmental protection issues, so new methods or processes are urgently needed. In view of this, this paper proposed and designed an experimental study of microbially modified expansive soil. The study found:

After the improvement of Nanning expansive soil using MICP technology, the free, unloaded and 100kPa loaded swelling rates of the expansive soil all have been significantly reduced. Various swelling indices showed that the soil sample no longer belongs to expansive soil after improvement.

The MICP technology can significantly reduce the liquid limit moisture content, plastic limit moisture content, and plasticity index of the expansive soil. After the improvement, the indices such as liquid limit moisture content and plasticity index obtained from the test show that the expansive soil is no longer a high liquid limit soil.

Through the study of the high-pressure consolidation test (including 12.5 kPa) with the change of the dry-wet cycle, it was found that after the improvement of the MICP technology, both drying-induced and wetting-induced moisture contents of the expansive soil samples were significantly reduced, indicating that their hydrophilic capacity was significantly weakened. Also, after the MICP improvement, the soils' axial deformations were significantly reduced, irrespective of being immersed or drained. This is due to the microbially induced calcium carbonate precipitation to result in the significant solidification of the expansive soil. Moreover, under different dry-wet cycles, the swelling and shrinkage rates of the expansive soil samples were consistent with the microbial solution treatment times. Particularly, when the number of treatments reaches six times, the swelling and shrinkage rates both reach the minimum.

In a word, the MICP technology has been showed to significantly improve a series of physical and mechanical properties of the expansive soil, and the improvement effect has a clear relationship with the concentration of the microbial solution or the number of microbial solution treatments. From our tests, after six treatments, all relevant indices of the expansive soil achieve the best improvement. Our current preliminary study reveals a new efficient way to improve the expansive soil for embankment and similar engineering alike with MICP technology.

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