

Experimental Study on Mechanical Properties of Microbially Modified Slag Based on CT Technology

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Abstract

This paper investigates the influence of Microbe-Induced Calcium Carbonate Precipitation (MICP) technology on the mechanical properties and permeability characteristics of solidified slag soil, with a focus on exploring the synergistic mechanism of key factors such as initial dry density, cementing solution concentration, and grouting rounds. The results indicate that a lower initial dry density is more conducive to the uniform generation of calcium carbonate and pore filling, significantly reducing the permeability coefficient of the sample and avoiding fracture; whereas an excessively high dry density tends to lead to uneven distribution of calcium carbonate. Simultaneously, the unconfined compressive strength increases exponentially with the increase in cementing solution concentration and grouting rounds, with the most significant strengthening effect observed when the concentration is 2.0 mol/L and the grouting rounds exceed 4. Microstructural analysis reveals that an appropriate amount of calcium carbonate precipitation can effectively fill pores, reducing the porosity to below 10.02%, decreasing the average pore size, and optimizing pore distribution, thereby enhancing soil compactness and mechanical properties. However, excessive grouting can lead to an increase in large-pore-size pores and a complex pore structure due to decreased reaction efficiency, which is detrimental to strength development. This study provides a theoretical basis for the optimized application of MICP technology in slag soil solidification.

Keywords: MICP; Waste soil solidification; Permeability coefficient; Microstructure.

Introduction

With the in-depth implementation of the “Belt and Road” and the “14th Five-Year Plan”, China will intensify the construction and development of the western economy, promote the coordinated development of the region, implement the strategy of developing the western region, promote the comprehensive revitalization of the western region and sustainable development, and lay a solid foundation for the realization of high-quality economic development. This will lay a solid foundation for the realization of high-quality economic development. Ertok Banner in Erdos City plays an important role in the small triangle economic circle in the western part of Inner Mongolia Autonomous Region, and as part of the Hubao-Erdao coordinated development strategy, it shows

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strong competitiveness and influence, and is a noteworthy county economy with rich mineral resources. In recent years, Ertuoqqi vigorously carry out the construction of green mines, in order to keep the ecological red line at the same time to guard the bottom line of development, the former devastated mines revitalization, an ecological and economic development of a beautiful picture scroll at the foot of the western mountains in the Uygurindu stretches. However, because mineral resources are non-renewable resources, with the gradual increase in the scale and intensity of people's mining and utilization, many kinds of mineral resources and some raw materials are on the verge of depletion, and all kinds of solid wastes continue to accumulate, for the ecological environment is unimaginable damage. Therefore, under the perspective of sustainable development, the use of microbial-induced calcium carbonate precipitation (MICP) technology to solidify mine spoils, as a new type of environmentally friendly soil reinforcement technology, through the urease enzyme produced by bacteria to hydrolyze urea to produce , which combines with the of the surrounding environment to generate calcium carbonate crystals to fill in the pore space between the soil particles, so that the soil samples are bonded together, to achieve the effect of reinforcing the soil, and then to improve the Mechanical properties of soil [1].

However, the effect of MICP consolidation of soils is limited and influenced by many factors, Oliveira et al. analyzed the effect of soil type on the microbial-induced calcium carbonate precipitation process and found that in sandy and chalky soils, calcium carbonate precipitation enhanced soil consolidation, while in organic soils, it had a deleterious biostabilizing effect [2]. Gao Yufeng et al. used microorganisms to cure standard sand surfaces, and found that appropriately increasing the volume and concentration of cementing liquids and the concentration of bacterial fluids can improve the MICP curing effect [3]. Ming Daogui et al. used a variety of calcium sources for the curing of windlogged sand and found that calcium chloride can effectively cure windlogged sand and has good mechanical properties and penetration ability [4]. Wang Teng et al. found that by changing the grouting method, utilizing the gradient difference in the particle size of the sand column, the calcium carbonate crystals were distributed more uniformly, and the permeability of the porous medium was significantly improved [5]. At present, the research on microbial curing of soils is mostly focused on sandy soils, and very little research has been done on microbial curing of slag soils, so it is necessary to carry out research related to the mechanical properties of microbial improvement of mine spoils.

In recent years, more and more experts and scholars have radically investigated the soil properties and micro-mechanisms by using a combination of macro and micro approaches, and performed cross-scale correlation and multi-scale analysis of micro-properties [6,7]. The advantages of CT scanning technology with its capability of structural non-destructive testing, holistic measurements and high resolution make it mostly focused on the porosity and micro porosity characteristics of geotechnical materials, particle size and shape properties, as well as the pattern of

fracture development and strain localization at present [8]. Zaidi et al. used CT technique to test the development of cleavage in fine-grained soils under dry and wet cycles [9]. Song Xiaoxia and others constructed a seepage pore model of coal specimen with the help of micro-CT technology, and studied the evolution laws of porosity, pore surface area and pore volume of coal specimen under different loading paths [10]. Based on the original CT images, Li Bo and others constructed a realistic two-dimensional GBM model of granite specimens and studied the expansion path of cracks in rock samples, starting from the distribution state of each component inside the rock [11]. There is little research on the microstructure of MICP-amended mine spoils, and there is a lack of systematic analysis of the pore structure complexity and distribution location.

In summary, this paper will study the effect of different binder concentration and different number of filling rounds on the strength characteristics of microbial improved mine spoils through the unconfined compressive strength test, and carry out the microstructure characteristics test with different number of filling rounds based on the industrial CT scanner and SEM, to analyze the change rule of spoils' porosity, pore diameter, fractal dimension and other rules, and to deeply carry out the research on the effect of number of filling rounds of binder on microstructure of mine spoils. Research on the influence of the number of cement filling wheels on the microstructure of mine spoils.

Materials and Methods

Mine spoils used for testing

The slag used in this test comes from a mine waste in Ertuoqqi, Ordos City, 5 sampling points were selected with coordinates (N111.236°, E39.868°), according to the test results of the indoor test, it can be obtained that the maximum dry density of the slag = 1.913, the optimal moisture content = 9.26. The gradation curve of the slag soil sample measured by sieving method is shown in figure 1, and its inhomogeneity coefficient $C_u = 11.7 (>10)$, $C_c = 1.65 (1\sim3)$, according to the "Standard for Geotechnical Test Methods" GB/T 50123-2019 can be located in the mine slag soil gradation is good [12].

Curing strains

The test was conducted using *Bacillus bacillus* as the strain, the concentration of which was expressed as OD_{600} (which refers to the absorbance value of the bacterial suspension at 600 nm wavelength), and the bacterial culture, expanded culture, and extraction methods were referred to the existing studies [13]. The liquid medium for the bacterial broth was selected from the LB formulation which mainly consisted of: yeast extract (20g/L), $(NH_4)_2SO_4$ (10g/L), urea (20g/L) and deionized water. The growth characteristic curve of *Bacillus subtilis* was tested using spectrophotometer as shown in figure 2. It can be found that at 0~2h, the bacterial cells start to divide and grow slowly, which is in the growth retardation period and the bacterial concentration is low; In 2~12h the bacteria are in logarithmic growth period, the bacteria have adapted to the environment and started to divide in large numbers, growing

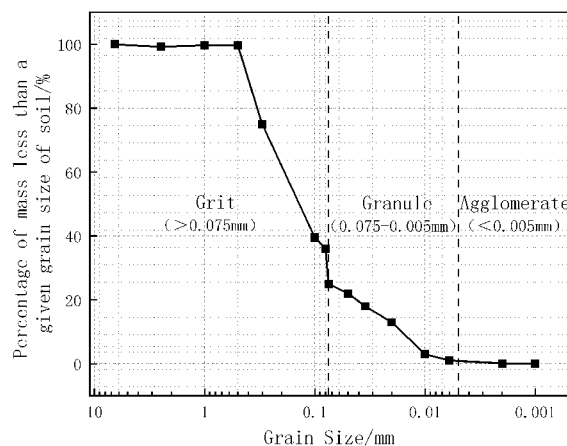


Figure 1: Mine spoils particle distribution curve.

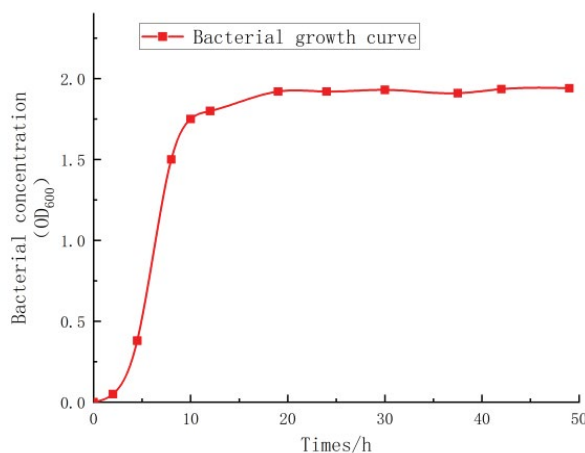


Figure 2: Growth Characterization Curve of *Bacillus subtilis*.

in a geometric progression, and in 12~48h they enter the stabilization period, where the bacterial proliferation and death tend to be in a dynamic equilibrium. Therefore, the OD600 of the bacterial solution used for curing sludge in this test was 1.9-2.0 and the incubation time was 48h.

Experimental design

Microbial-catalyzed urea hydrolysis for soil reinforcement is a very complex biochemical process, and there are numerous factors that influence this reaction process resulting in different physico-mechanical properties of the amended soil specimens. The urease secreted by *Bacillus pasteurus* catalyzes the hydrolysis of urea, producing NH_4^+ and CO_3^{2-} ions, which react with Ca^{2+} ions in an alkaline environment to produce calcium carbonate crystal precipitates. Differences in cement concentration affect the urea hydrolysis reaction and at the same time greatly influence the calcium carbonate precipitation process [14]. In order to investigate the effect of binder concentration on the mechanical properties of microbiologically cured mine spoils, the binder materials selected in this experiment were

urea ($CO(NH_2)_2$) and calcium chloride ($CaCl_2$), and the binder was configured as a mixture of $CO(NH_2)_2$ and $CaCl_2$, and the binder was designed to be of three different concentrations of 1.5mol/L, 2.0mol/L and 2.5mol/L ($CaCl_2:CO(NH_2)_2=1:1$).

Preparation of slag soil specimen first take a certain amount of soil material for natural air drying after sieving and into the dryer to dry, followed by the use of mixing the soil box bacterial liquid uniformly and fully mixed, divided into five layers of uniformly paved to the size of 39.1mm * 80mm acrylic mold, each layer of the use of a compacting hammer to solidify the scraping until both ends of the smooth and flat without obvious depression phenomenon, prepared specimen static 24h later Filling of cementing liquid.

Results

Penetration test

According to the "Standard for Soil Test Methods" GB/T 50123-2019, permeability tests are conducted on solidified soil samples [12]. Figure 3 shows the relationship curve between the permeability coefficient of solidified slag and

the number of cementing cycles under different initial dry densities. During the experiment, it was found that the samples with initial dry densities of 1.7g/cm^3 and 1.8g/cm^3 often exhibited fracture phenomena. The main reason for this phenomenon was the uneven distribution of calcium carbonate. When the bonding solution was injected, CaCO_3 crystals first formed near the infiltration port and gradually accumulated. With the increase of bonding times, the samples were blocked near the infiltration port, while the solidification effect was poor far away from the infiltration port, ultimately forming a fracture surface at the junction of the two points. As shown in Figure 3, compared with the initial permeability coefficient, the permeability of the MICP solidified slag soil sample significantly decreases, and the permeability coefficient decreases with the increase of dry density. The main reason is that the generation of CaCO_3 crystals fills the pores between sand particles, causing the originally loose sand particles to bond into a whole, reducing the permeability path and significantly reducing the permeability of the sample. As the number of cementing cycles increases, the amount of CaCO_3 crystals generated gradually increases, and the permeability coefficient continues to decrease. For the slag soil samples with initial dry densities of 1.5 g/cm^3 and 1.6 g/cm^3 , the permeability coefficient is the smallest when the bonding times are 10, reaching $6.02 \times 10^{-4}\text{ cm/s}$ and $1.12 \times 10^{-4}\text{ cm/s}$ respectively, indicating that CaCO_3 crystals continue to form with the increase of bonding times, continuously filling the pores between sand particles, resulting in a gradual decrease in permeability.

The amount of CaCO_3 generated is an important indicator for evaluating the solidification effect of MICP, which has a significant impact on the permeability and strength characteristics of solidified soil samples. Figure 4 shows the relationship curve between the amount of CaCO_3 generated and the number of cementing cycles for solidified aeolian sand samples under different initial dry densities. As shown in the figure, the amount of CaCO_3 generated increases with the increase of bonding times, indicating that CaCO_3 continues to be produced with the increase of bonding times,

which is consistent with the results of the permeability test. For wind-blown sand samples with different dry densities, when the initial dry density is 1.5g/cm^3 and 1.6g/cm^3 , the CaCO_3 content produced after MICP solidification is relatively high, with formation rates reaching 0.21g/g and 0.19g/g , respectively. The main reason is that when the dry density is low, the sand particles are relatively loose, providing sufficient space for MICP mineralization reaction, which facilitates the reaction between bacteria and cementing fluid to generate CaCO_3 crystals.

Unconfined compressive strength test results

Unconfined compressive strength (UCS) is an important parameter reflecting the strength of the soil body, and the two parameters of binder concentration and the number of rounds of binder infusion were used as the variables of the specimen to carry out the UCS test, and the test results are shown in figure 5.

With the increase of the number of cement filling rounds, the compressive strength of the specimens with different cement concentration showed a trend of slow increase and then rapid increase, and the compressive strength maintained an exponential growth relationship with the number of cement filling rounds. As a whole, the compressive strength showed a gradual incremental trend during the gradual increase of the number of infused binder rounds from 0. For the specimens with binder concentrations of 1.5 mol/L , 2.0 mol/L , and 2.5 mol/L , the compressive strengths were increased by 67.93%, 74.86%, and 75.37%, respectively, which can indicate that with the increase of binder concentration, the microbial compressive strength of the modified specimens increased significantly. Among them, when the number of filling rounds was increased from 0 to 4 times, the compressive strength increased relatively slowly, and for the specimens with cement concentration of 1.5 mol/L , 2.0 mol/L , and 2.5 mol/L , the compressive strength increased by 21.68%, 31.63%, and 28.87%, respectively. It can also be seen from figure 5 that the strength of the improved specimen increases rapidly after the number of filling rounds reaches 4 times, indicating that the increase

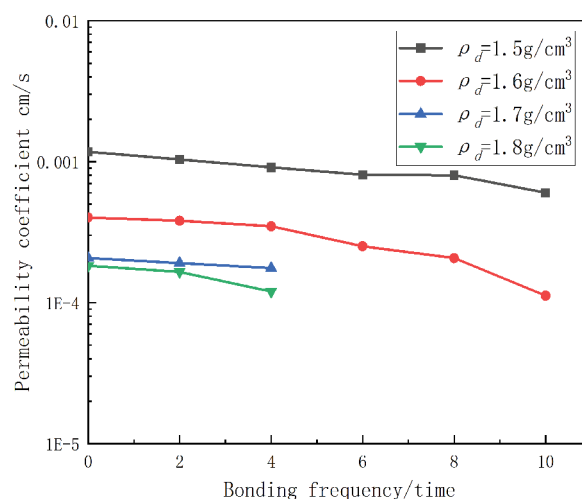


Figure 3: Relationship curve between permeability coefficient and cementation frequency.

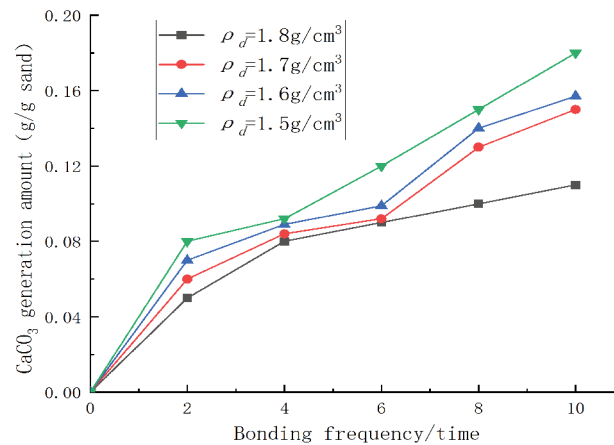


Figure 4: Relationship curve between CaCO₃ generation and bonding frequency.

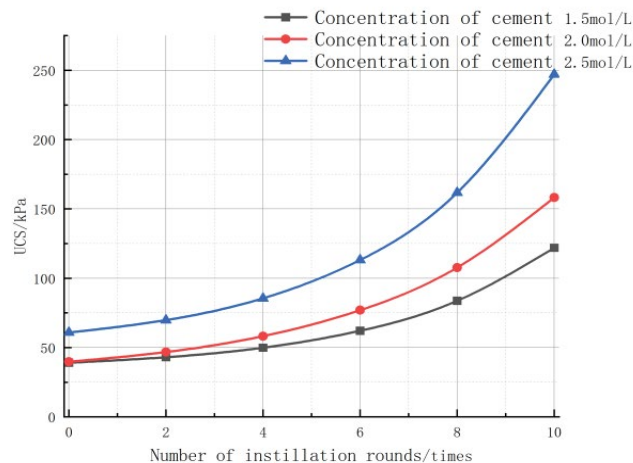


Figure 5: Influence of the number of rounds of cement infusion on the compressive strength of microbiologically improved residual soils.

in the number of filling rounds of cementing liquid can effectively reduce the loss of compressive strength, and the effect of the number of filling rounds on the mechanical properties of microbial cured residue is slower up to 4 times, and there is a more pronounced increase in the mechanical strength of the improved specimen after it reaches 4 times.

The modulus of elasticity of the specimens with different cement concentration after going through different number of filling rounds is shown in figure 6. Instead of the modulus of elasticity in this test being the cutline modulus, the ratio between the 50% peak stress and its corresponding axial strain was used [15]. When the number of filling rounds is 0-2 times, the difference between the modulus of elasticity of the specimens with different cement concentration is small, and the cementing ability between particles is weak, flexible, and the modulus of elasticity is large when the number of filling rounds is less; When the number of filling rounds reached 4 times, the elastic modulus of the specimens with different concentrations of cementing

liquid were significantly reduced, and the elastic modulus of the specimens with a cementing liquid concentration of 1.5 mol/L showed a rapid trend of decreasing, compared with the specimens with different concentrations of the elastic modulus of the specimens with the largest, which was due to the generation of calcium carbonate crystals with less content of its flexibility is higher. As a whole, with the further increase in the number of filling rounds, the relatively large fluctuations in the modulus of elasticity is due to the generation of calcium carbonate crystals caused by pore changes and the aggregation of the structure between the particles, so the number of filling rounds of 0-2 times the modulus of elasticity tends to be relatively stable, the reinforced specimen due to the cementing liquid due to the rapid increase in the content of calcium carbonate generated by the mixing of the cementing effect between the particles to make it have a good compressive strength and Deformation ability. Combining the effects of the two factors on the unconfined compressive strength, it can be seen that the strength is highest when the cementing liquid

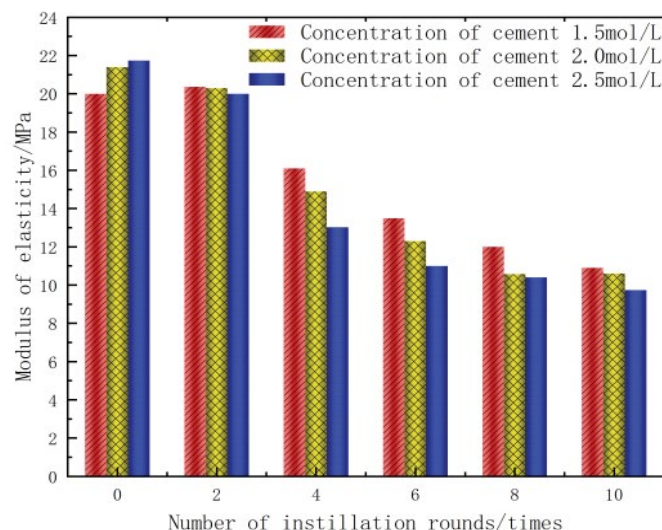


Figure 6: Changes in modulus of elasticity of improved specimens with different number of filling rounds.

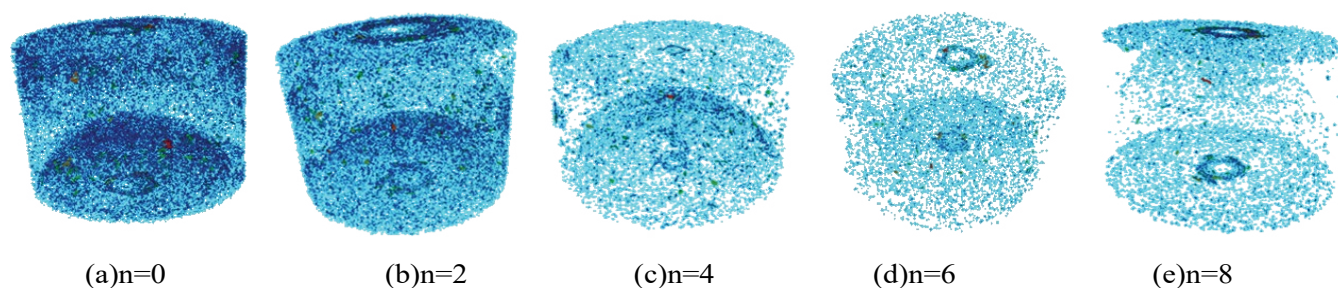


Figure 7: CT image.

is 2.0 mol/L, and the compressive strength has a significant increasing trend after the number of filling rounds reaches 4 times.

After the cementing liquid and bacterial liquid cycle added to the soil, with the maintenance process, the calcium ions in the cementing liquid combined with carbonate ions, precipitation of calcium carbonate crystals, more and more crystals will be deposited to wrap the bacteria, and ultimately the formation of the bacterial body as the nucleus, with the role of the biological cementing liquid of calcium carbonate cements and thus curing the geotechnical substrate [16].

CT Test results and discussion

This test utilizes the model FF35 high-precision industrial CT scanner produced by German YXLON, which has a maximum target output power of 280W, a maximum focal length of 1160mm, and a geometric magnification of up to 175 times. In order to study the effect of the number of binder infusion rounds on the mechanical properties and microstructure of microbially cured mine spoils, specimens with 0, 2, 4, 6 and 8 infusion rounds at a binder concentration of 2.0 mol/L were selected in this paper, and their microstructural properties under the effect of different binder concentrations were tested by CT scanning

technology. The continuous grayscale images obtained after CT scanning are processed using 3D software, and in this paper, the binarized images are processed using threshold segmentation employing the trial-and-error method [17].

As can be seen from figure 7, the pores of the modified specimen are distributed on the surface of the specimen, the closer to the surface of the specimen the more pores, this is due to the penetration of the bacterial fluid into the interior of the specimen, the surface and the cementing liquid did not react sufficiently, the generation of calcium carbonate crystals is less therefore the pores have not been uniformly filled; The pores inside the specimen were distributed in a semi-curved shape, due to the use of artificial compaction of the way to compact the residual soil and compacting hammer is not uniform, in a certain number of times under the compaction of the soil body is difficult to compact the soil particles between the existence of pore space. Among them, the change of the number of pores is relatively small when the number of filling rounds $n=0$ and $n=2$, and the number of pores is obviously reduced compared with $n=4$, $n=6$ and $n=8$. The more the number of filling rounds is, the less the number of pores is inside the specimen.

Table 1 shows the change rule of porosity of specimens

after reinforcement with different number of filling rounds. As a whole, the porosity showed a decreasing and then increasing trend as the number of filling rounds increased. When the specimen experienced two rounds of filling, the reduction of its porosity reached a maximum of 16.8%, and when the number of rounds of cementing liquid was 6 times, the porosity reached a minimum of 10.02%, which can indicate that the increase in the number of rounds of cementing and filling can effectively fill the pore space, thanks to the fact that a large amount of calcium carbonate precipitation was produced on the surface of the residue particles and between the pore spaces, which effectively strengthened the adhesion of the particles of the soil body, and reduced the pore space between the particles. and at the same time consolidate the upper soil particles into a hard shell layer with a certain thickness and strength, substantially increasing its strength [18]. The porosity of the specimens with different number of filling rounds decreased by 10.93%, 25.90%, 38.80%, and 40.56%, respectively, compared with the number of filling rounds $n=0$. The difference in porosity between $n=0$ and $n=2$ is relatively small, which indicates that the microstructure inside the slag is slightly affected in the case of less number of filling rounds. The decreasing trend of porosity gradually slows down at $n=6$ and $n=8$. Although too much cementing liquid can effectively fill the pore space of the residue, but due to the number of ions in the soil is limited, the cementing liquid can't be sufficiently combined with Ca^{2+} , so it can't be filled with a large number of which leads to a reduction in the efficiency of its reaction.

From figure 8, it can be seen that the pore diameters at $n=0$ and $n=2$ all show bimodal distribution, and the

pore diameters at $n=4\sim8$ all have Gaussian distribution, which can be concluded that the difference in the number of cement filling rounds can make the distribution of pore diameters more uniform. The pore diameters at $n=0$ and $n=2$ were concentrated between the ranges of 210-240 μm and 180-210 μm , respectively, with a percentage of 36% and 27%. When the number of filling rounds n reaches 4, the pore diameter is centrally distributed in 120~150 μm , while the percentage of small-diameter pores gradually increases, with less than 90 μm diameter pores increasing by 7.5% compared to that at $n=0$, and greater than 180 μm pores accounting for 21%. With the increase of the number of filling rounds, the diameter pores with the highest proportion of $n=4$ and $n=6$ are decreasing, which is due to the fact that the generated calcium carbonate crystals can effectively fill the pores between the soil particles, so the filling of the appropriate number of rounds of cementing liquid can effectively reduce the diameter of the pores; When $n=4$ the pores smaller than 90 μm accounted for 23%, and greater than 180 μm accounted for 21% of the pore diameter approximated to the small pore diameter, which can be demonstrated that the number of filling rounds of 4 specimens of the pore more uniform; However, when $n=6$ there are fewer pore diameters larger than 180 μm (26%) than those smaller than 90 μm (11%), and an increase in small pore diameters and a decrease in large pore diameters can increase the compactness of the soil and change the strength of the internal skeleton of the soil. However, when the number of filling rounds is too many, the number of large-diameter pores increases, the proportion of small-diameter pores decreases, and the proportion of the largest

Number of instillation rounds-n (times)	0	2	4	6	8
Porosity-m(%)	16.37	14.58	12.13	10.02	9.73

Table 1: Trends in porosity with different number of filling rounds.

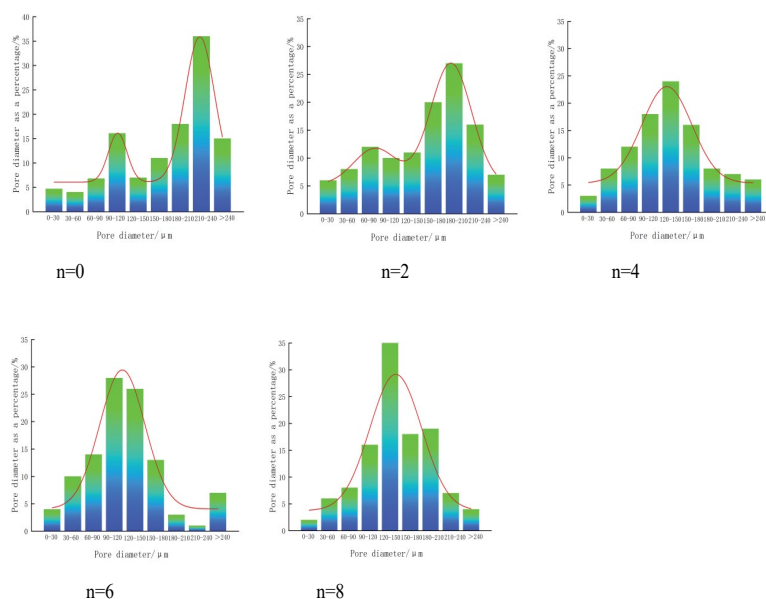


Figure 8: Pore diameter variation.

pore diameter of 120~150 μm reaches 35%. Due to the limited content of bacterial fluid, the participation of too much cementing liquid will lead to its inability to effectively combine with CO_3^{2-} , and then the pore diameter inside the soil body increases, which weakens the mutual attraction between the soil particles.

The significance of fractal dimension is that it can reflect the complexity of soil pore structure, i.e., the larger the fractal dimension is, the more pore space is developed and the more complex the pore structure is, which was introduced to quantitatively study the characteristics of its pore structure [19]. The variation of fractal dimensions and maximum and minimum fractal dimensions at different locations were extracted using the built-in differential box dimension algorithm for 3D image processing software, where the number of slices 0 sheets represents the bottom of the specimen and the number of slices 400 is the top of the specimen [20].

From figure 9 and table 2, the fractal dimension distribution of the specimens with different number of filling rounds is between 0.47 and 2.04, which indicates that the pore structure of the slag specimen is relatively simple after microbial treatment. The fractal dimension on 248~267 slices shows a wave peak, which is the result of layered compaction, and this peak is located in the fourth layer of compacted soil, because the previous layer is denser after compaction, so it can't be well bonded together after scraping, moreover, the soil also occurs layered inhomogeneity, which is the reason why the pore structure is more complex in this area [21]. However, the formation of multiple pores at the top position of the sample reflects a more complex pore structure on the one hand, because at the top only by compaction, there is not yet the gravity of soil particles crowded soil, on the other hand, because of the bacterial liquid penetration into the interior of the specimen, the surface of the bacterial liquid only a small amount of calcium carbonate crystals generated by the combination of the bacterial liquid and cementing

liquid to fill the pore space, which appeared to have a more complex pore structure.

The fractal dimension of the pores after the number of filling rounds n reaches 2 times are smaller than the specimens with $n=0$. The magnitude of change of fractal dimension decreases and then increases as n increases. The variation of fractal dimension is slowest in the case of $n=4$, and the average fractal dimension reaches 0.85. The trends of maximum, minimum and average values of fractal dimension are consistent with the variation of specimens at different locations. Compared with $n=0$, the fractal dimension of specimens with different number of filling rounds decreased by 4.38%, 37.96%, 32.85%, 63.50% on average; the maximum value decreased by 0.49%, 14.71%, 10.29%, 11.76%; the minimum value decreased by 21.62%, 36.49%, 31.08%, 32.43%, and the data show that filling the appropriate amount of rounds of cementing liquid can effectively reduce the fractal dimension and thus reduce the complexity of pore structure, and achieve the effect of improving the mechanical properties of soil.

SEM analysis

SEM images of the specimens with magnification of 1k times at different number of filling rounds are shown in figure 10. As can be seen from the figure, the specimen infused with cementing liquid rounds of 0 (Fig 10 (a)) appears to have connected pores and weak cementation between particles; after the number of filling rounds increases to 2 (Fig 10 (b)), calcium carbonate crystals appear to fill the pores, but due to the small number of filling rounds, a large number of pores still exists; after the number of filling rounds increases to 4 (Fig 10 (c)), the soil particles form a more stable structure, and the pore distribution is more When the number of filling rounds is 6 times (Fig 10 (d)), a small number of calcium carbonate crystals begin to gradually wrap the particles, and the pores in the specimen are gradually reduced; when the number of filling rounds reaches 8 (Fig 10 (e)) times, a large number of calcium carbonate crystals are generated,

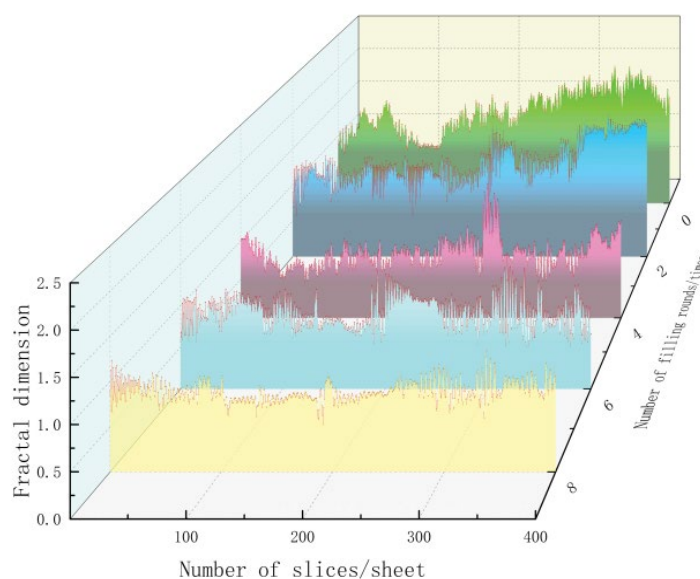


Figure 9: Fractal dimensions at different positions.

Pore diameter as a percentage/times	The maximum value of fractal dimension	Minimum fractal dimension	Average fractal dimension
0	2.04	0.74	1.37
2	2.03	0.58	1.31
4	1.74	0.47	0.85
6	1.83	0.51	0.92
8	1.80	0.50	0.9

Table 2: Law of change of fractal dimension.

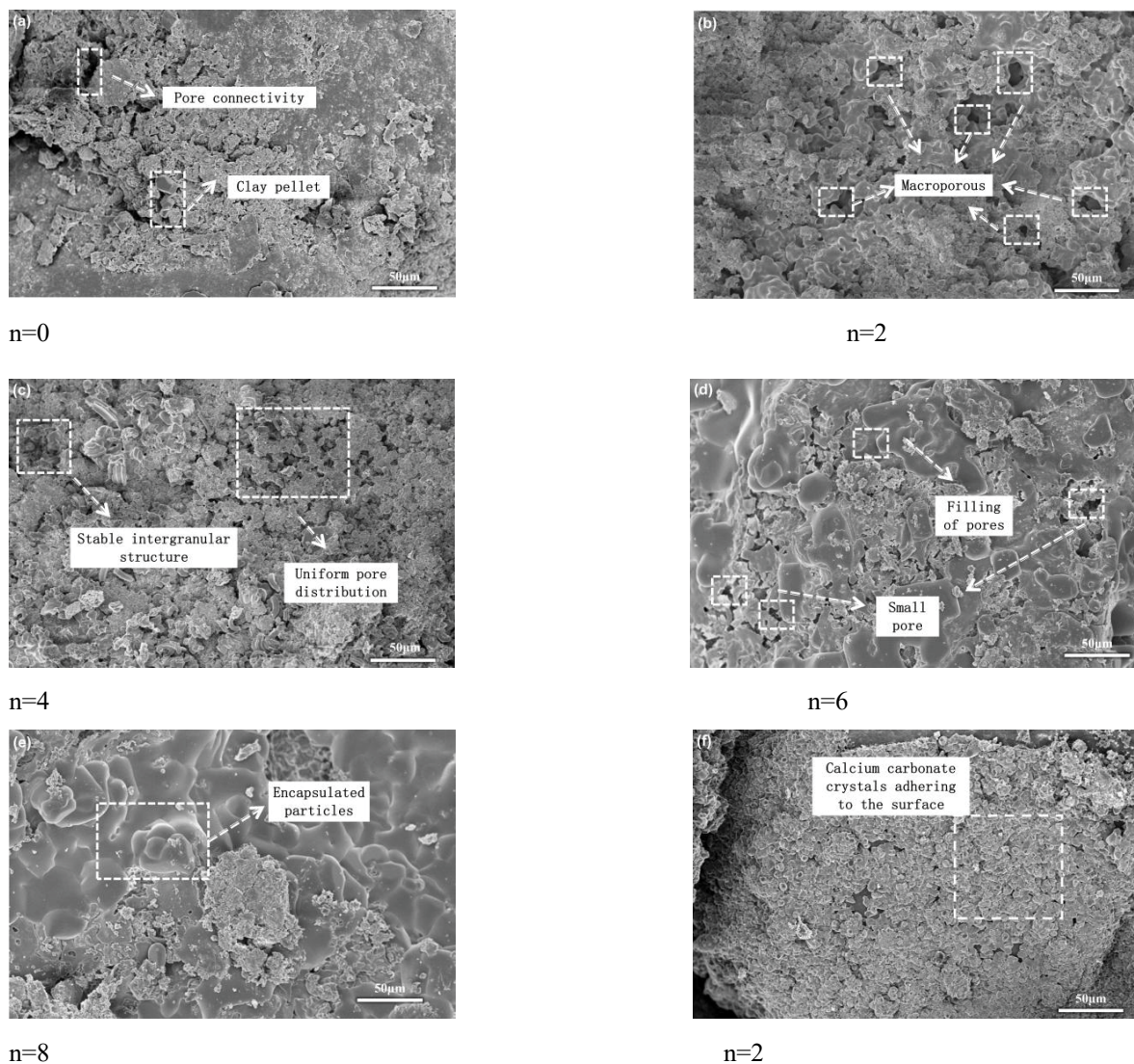


Figure 10: SEM test results.

wrapping the soil particles and gluing adjacent particles together, so that the loose soil is completely covered by calcium carbonate crystals to form a solidified body of a certain strength. In order to verify the CT meter results showing a large number of pores on the surface of the specimen, in this section, SEM was used to scan the surface of the specimen with 2 perfusion rounds and the SEM results, as shown in fig 10 (f), show that there are a large number of calcium carbonate crystals attached to the surface of the specimen, and there are very few effective connections between the calcium carbonate and the soil particles, thus generating a large number of pores between the particles.

Calcium carbonate precipitation was generated in the specimens with different number of filling rounds, and calcium carbonate filled in the pores of soil particles, formed effective connection between particles, and cemented the loose residue into a whole, which verified the feasibility of MICP technology in reinforcing mine residue. However, the calcium carbonate generation varies with the number of perfusion rounds, and the calcium carbonate generation increases with the increase of the number of perfusion rounds, which is consistent with the results shown by the CT meter. MICP curing is a continuous accumulation process, when the number of filling rounds increases when the calcium carbonate crystals accumulate in large quantities

and gather into clusters, wrapping and covering the soil particles and filling the pores between the soil particles, so that the particles form an effective cementation and thus the specimen forms a curing body with a certain degree of strength.

Conclusion

The following conclusions were obtained by carrying out mechanical characterization tests on specimens infused with different rounds of cementing fluid at different cementing fluid concentrations and analyzing the microscopic characteristics of the specimens using CT scanning technology and SEM scanning electron microscopy:

(1) The initial dry density and the number of cementation cycles synergistically affect the solidification effect and permeability: MICP technology can effectively reduce the permeability of solidified slag soil samples. The permeability coefficient decreases with the increase of cementation cycles and initial dry density. However, excessively high dry density (1.7 g/cm^3 and 1.8 g/cm^3) tends to cause sample fracture due to uneven distribution of calcium carbonate, while lower dry density (1.5 g/cm^3 and 1.6 g/cm^3) is more conducive to calcium carbonate formation and pore filling, achieving a better solidification effect;

(2) Collagen solution concentration and grouting rounds synergistically enhance compressive strength: The unconfined compressive strength of microorganism-solidified slag soil significantly increases with the increase in collagen solution concentration and grouting rounds, and there is an exponential growth relationship between the two. When the grouting rounds exceed 4 times, the compressive strength shows a rapid growth trend, with the optimal strengthening effect achieved when the collagen solution concentration is 2.0 mol/L .

(3) Microscopic pore structure effectively improves and influences mechanical properties: CT scanning and SEM analysis indicate that as the number of cementation fluid infusion rounds increases, the generated calcium carbonate crystals can effectively fill inter-particle pores, reducing porosity (down to a minimum of 10.02%) and average pore diameter, and making the pore distribution more uniform. Fractal dimension analysis further confirms that appropriate infusion can significantly reduce the complexity of the pore structure, thereby enhancing soil compactness and strength.

(4) Excessive infusion leads to a decrease in reaction efficiency and deterioration of pore structure: When the number of infusion rounds is excessive, due to the limited reaction efficiency of the bacterial solution and ions, the excess cementing fluid cannot be fully converted, which instead leads to an increase in the proportion of large-pore-diameter pores, a rise in fractal dimension, and a complex pore structure, adversely affecting strength gain and uniformity.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Ethical Approval

The article does not involve this work content.

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