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Comparative Study on Strength and Permeability of Siliceous Sand Treated by MICP and Cement Grouting

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ABSTRACT: Cement and other chemical materials are widely used as additives in soil improvement. Microbially induced calcite precipitation technology has been used in soil improvement as the advantage of green and environmental protection. In this study, the potential of using microbially induced calcite precipitation (MICP) technology replaces cement for treating siliceous sand is presented. A series of laboratory tests were carried out to assess the unconfined compressive strength (UCS) and permeability of microbial-reinforced sand and cement-reinforced sand. The results indicated that, for the experimental siliceous sand with a small particle size (0.63-1.25 mm), the average UCS of the microbial-reinforced sand is significantly higher than that of the cement-reinforced sand under the condition of curing for 7 days, and the quality of cement-reinforced sand is affected by the water-cement ratio. The permeability coefficient of microbial-treated sand is also significantly reduced, which are 0.0007 times and 0.05 times that of pure sand and cement-reinforced (w/c = 2:1), respectively. The porosity reduction of the sample after microbial grouting is up to 13.6%, which is also significantly higher than cement-reinforced. The microstructure study shows that calcite crystals can not only be widely attached to the surface of sand particles, but also better penetrate into the voids between sand particles, formed more effective ways of connection and make more effective bonding. It explains why microbial-reinforced sand has higher unconfined shear strength and lower permeability coefficient than cement-reinforced sand.

KEYWORDS: Siliceous sands, MICP, Cement grouting, Unconfined compressive strength, Coefficient of permeability.

1. INTRODUCTION

Cement-grouting and cement-mixing is commonly used for soil improvement in geotechnical engineering, where soft soils need to be stabilized to prevent unacceptable deformations or fluid flow (Chai et al., 2005; Horpibulsuk et al., 2012; Wang et al., 2016; Zhang et al., 2018; Pascual-Muñoz et al., 2018; Yi et al., 2018; Yao et al., 2019; Wei and Ku, 2020; Kou et al., 2021). Over the past few decades, Portland cement has been widely used as a traditional grouting material. The commonly used cement particle size range for grouting is 10-45 μm, compared with the pores between soil particles, the size of cement particles is large and poor fluidity. In the process of grouting, that may block the grouting tubes and reduce the efficiency of grouting. (Saada et al., 2006; Kim et al., 2009; Wang et al., 2013; Subramanian et al., 2018 Yang et al., 2020). Many researches have been done on additives to be incorporated into the cement slurry to solve the problem of workability. However, most of them are chemical additives, which is bad for harmful to people's health and the environment. (Rosquoet et al., 2003; Behnood et al., 2018; Kamei et al., 2018; An et al.,2018). Furthermore, the cement production process comes with a lot of CO_2 emission, which is the culprit of greenhouse effect. According to the statistics, the cement industry accounts for about 6% of all CO_2 emissions, since making one ton of cement emits one ton of CO_2 into the atmosphere. (Cristelo et al., 2013; Phanikumar and Raju, 2020; Kou et al, 2021) Hence, in practice, there is a high demand for eco-friendly materials and technology that may replace cement in grouting.

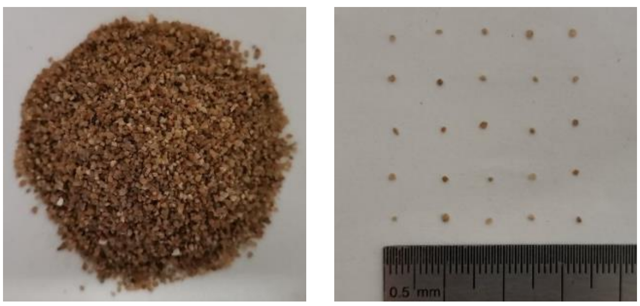
In the early 2000s, Mitchell and Santamarina (2005) pointed out that microbial activities can affect the formation and properties of soil, such as microstructure, strength, stiffness, permeability, etc. and the diameter of bacteria is about 0.5~3 μm, even more, the spore diameter of bacteria can be as small as 0.2 μm. Compared with cement grouting, microorganism has incomparable advantages. Along with the study of microbial technology going in-depth, an innovative soil improvement method, namely, microbially induced calcite precipitation (MICP) has emerged in the field of geotechnical engineering to ameliorate the problems mentioned above, aiming to reduce the permeability and liquefaction of saturated non-viscous soils (Whiffin et al., 2007; Van Paassen et al., 2010; Wang et al., 2012; Burbank et al., 2013; Li et al., 2015; Akyol et al., 2017; Zhang et al., 2018; Liu et al., 2020; Arpajirakul et al., 2021). Van Paassen et al. (2010) first isolated microorganisms from the soil to carry out a bio-cementing test on a 2.0 m long sand column, and then conducted tests on the foundation reinforcement of an underground gas pipeline. Gomez et al. (2015) applied MICP to strengthen the soil at a mine site in the province of Saskatchewan, Canada. Chu et al. (2012, 2014) carried out anti-seepage treatment with microorganisms by spraying bacterial suspension in the surface soil at the bottom of the reservoir, making the soil surface impervious to water. Muthuk kumaran, and Shashank, (2016) applied MICP technology to improve the behavior of the cohesionless soils. Zamani and Montoya (2018) studied the undrained monotonic shear response of silty sand treated by MICP, the results show that MICP method can significantly improve the shear strength of silty sand. Liu et al. (2020) applied MICP technology for the treatment of clayey soils on earth surface, and find that MICP is effective to increase the desiccation cracking resistance of soil. Kou (2020) conducted a series of bench-scale flume erosion tests on sandy slopes with MICP treatment, indicated there was interlocking cementation produced between sand particles in the sandy slope after MICP treatment, which contributed to reduce the permeability of sand. Arpajirakul et al. (2021) using the MICP method to stabilized swelling behavior and improving the mechanical property of expansive soil, confirmed the effectiveness of MICP. Apart from ground improvement, MICP method is also used for self-healing concrete. Jongvivatsakul et al. (2019) applied healing agent externally to cracked mortar samples by dropping bacteria and urea solutions daily. Based on the previous theory of MICP repair of mortar cracks, Pungrasmi et al. (2019) focused on determining a suitable microencapsulation technique to preserve bacterial spores. Intarasoontron et al. (2021) made a further comparison of the crack healing performances of biological self-healing concretes using cell/nutrient dropping and immobilization methods to produce MICP. Results indicated that the vegetative cell dropping method was more effective in closing cracks. The above studies indicated that MICP method has possessed sufficient feasibility and relatively high utility value.

However, there is a lack of comparative study on the treatment evaluation between MICP and cement grouting method, especially for the strength and permeability of reinforced sands. In this study, unconfined compression test and permeability test are carried out to prove the effectiveness of microbial grouting methods. The permeability coefficient and uniaxial compressive strength (UCS) of cement treated sand with different *w/c* ratio and microbial grouting samples were measured. The interface morphologies of bio-treated sand and cement-treated sand were observed using scanning electron microscopy (SEM).

2. MATERIALS

The siliceous sands used in this study were collected from a site off the east coast of Qingdao City, China (Figure 1). The physical properties of the sand are summarized in Table 1. The cement used in this study was 42.5 Ordinary Portland. The chemical composition of cement used is shown in Table 2. Two different water-cement ratios of 2:1 and 4:1 were adopted, respectively.

For bio-grouting, the bacillus *Pasteurella* was adopted (Sporosarcina. Pasteurii, number: ATCC11859). NH_4-YE liquid with 20.0 g/L yeast extract, 10.0 g/L $(NH_4)_2SO_4$ and 0.13 mol Tris-HCl was used as a medium, and its pH was maintained as 9.0. The activated bacteria were inoculated into the NH_4-YE liquid medium. At a temperature of 30 ℃ and speed of 150 r/min, the liquid medium used was cultivated in the concussion incubator until it appears to be turbid at 24 h. Thus, the used bacterial fluid was formed. In this paper, we use spectrophotometer to detect the number of microorganisms and the wavelength of detection is 600 nm, the measured value is represented by OD_{600}, and the measured OD_{600} value of bacterial solution is 1.753. The enzyme activity of the used bacterial liquid was 0.66 ms/cm/min by conductivity method. The nutrient solution was a mixture of 0.5 mol/L urea and $CaCl_2$, which can be used by bacteria to induce $CaCO_3$.



(a) (b)

Figure 1 Sand sample used in this study: (a) Sand dune and (b) Sand particles

Table 1 Basic physical properties of sand

Particle size (mm)	Specific gravity G_s	Relative density Dr (%)	Maximum dry density ρ_{dmax} (g/cm³)	Minimum dry density ρ_{dmin} (g/cm³)	Grain diameter d_{50} (mm)	Friction angle φ (°)
0.63 - 1.25	2.65	51.39	1.67	1.37	0.71	34

Table 2 Chemical composition of cement

Chemical composition	CaO	Al_2O_3	MgO	Fe_2O_3	SiO_2	SO_3
Percentage (%)	2.65	51.39	1.67	1.37	21.14	0.28

3. SPECIMEN PREPARATION AND TEXT METHODS

3.1 Test Specimen

Figure 2 illustrates the schematic diagram of cement grouting in this study. The acrylic tube used was 32 mm in inner diameter and 100 mm in height. It was first filled with sand using the sand pourer method and then tightly covered with caps. Two sealing rings were used on both the top and bottom, to prevent leakage in the grouting. A geotextile filter was placed between the sealing ring and the sand to prevent the particles from entering the hose. An air compression pump was connected with the mixing chamber to supply the required grouting pressure. As the peristaltic pump is used for biological grouting, the grouting pressure is small. In order to form contrast, the grouting pressure is set to 50 kPa. Air was pumped into the mixing chamber through pipe where the cement slurry was prepared in advance; then the slurry was injected into the grouting chamber to stabilize the sand samples. During the test, the grout volume is controlled at 500 ml each time. The grout should be prepared when using, mix fully and inject into the sand samples quickly, so as to avoid excessive precipitation during the static setting of the grout.

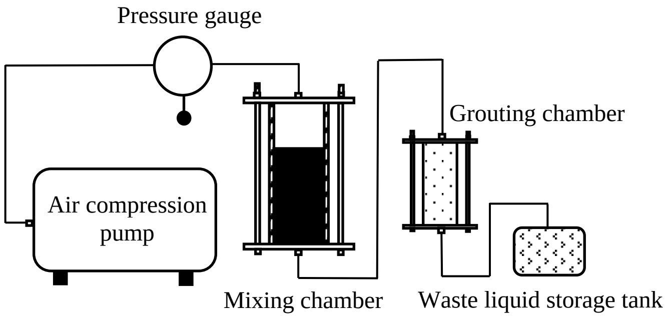
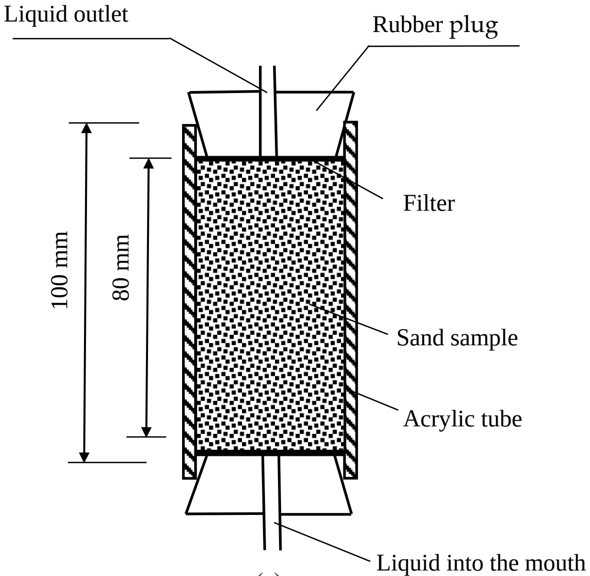


Figure 2 Schematic diagram of cement grouting (Bordier et al., 2000)

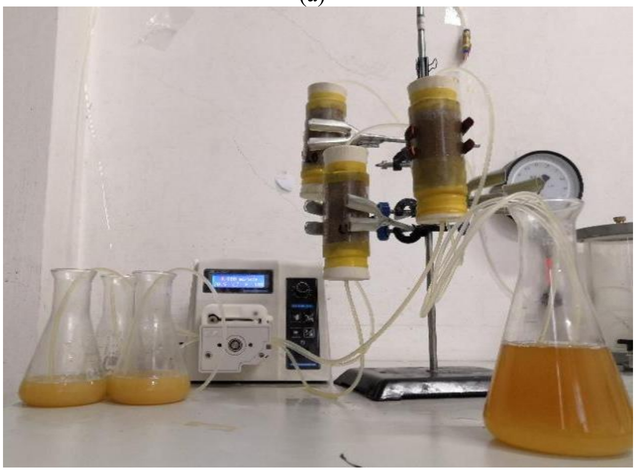
The microbial-reinforced specimen was prepared using a special grouting chamber, as shown in Figure 3. This chamber comprises an acrylic tube with an inner diameter of 32 mm and a height of 100 mm. Before grouting, sand samples were evenly poured into the acrylic tube using the sand pourer method. The bottom of the acrylic tube was sealed with a single-hole rubber plug. A geotextile filter was placed between the rubber and the sand to prevent the particles from entering the hose. It should be noted that the degree of compaction for cement and the bio-treated sands was kept consistent for the aim of comparison.

The peristaltic pump was adopted for bio-grouting and the grouting rate was 3.0 ml/min. A 100-ml mixture of bacteria solution and fixed solution (0.05 mol/L $CaCl_2$) were first injected into the sand samples from the bottom. After 5 h, 100 ml of the nutrient solution was injected. After 12 h, 100 ml of the nutrient solution was injected again. Then, the treated samples were tilted upside down and the injection from the bottom was continued. The above processes were repeated until the nutrient solution could not be injected into the sand samples again. 6 rounds of injection were performed in total. It takes 7 days to complete the 6 rounds of grouting. In order to form a comparison, the samples after 7 days of cement grouting curing were selected for the tests.

During the grouting test work, it is found that when the water cement ratio is inappropriate, there is an obvious siltation layer on the upper part of the sample during the grouting process (Figure 4), and the grouting pipe is blocked, resulting in poor reinforcement effect of the sample. This phenomenon can be explained: the particle size of grouting slurry and the particle size of sand sample. Previous studies show that ordinary portland cement has particles having an average diameter of 10-15 micrometers (Chu et al., 2013). After being mixed with water, the cement slurry tends to form a particle cluster with large adhesion. This will cause lower liquidity of the cement slurry and result in blocking the grouting tube. On the other hand, due to the small particle size of the sample sand, the gap between the sand particles is also small, which limited the flow speed of the cement slurry in the gap. During the grouting process, the cement slurry prematurely solidified on the upper part of the sample, resulting in channel blockage. the slurry cannot be evenly distributed among the sand particles, resulting in poor reinforcement strength of the sample. At the same time, this is also one of the important reasons for the blockage of the grouting pipe mentioned above.



(a)



(b)

Figure 3 Test setup for microbial-reinforced: (a) Sketch of MICP reinforced procedure and (b) MICP reinforced in the lab

According to the previous study of Kou et al., (2020) and Shan et al., (2022), the water cement ratio of 2:1 and 4:1 and bacterial cementing fluid concentration of 0.5 mol/L were selected as the cement grouting material and the in this study. The specific test group settings are shown in Table 3.

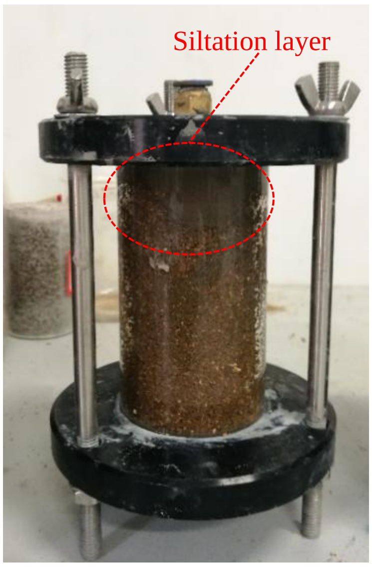


Figure 4 Channel blockage during cement grouting

Table 3 Test group setting

Test group	Reinforcement method	Water cement ratio (w/c)	Bacterial solution treatment
C-1	Cement	2:1	/
C-2		4:1	
M-1	Microbial	/	0.5 mol/L 6 times
M-2			
M-3			

3.2 Testing Methods

After sample treatment, measure the mass and size of the sample before and after treatment to calculate the porosity. The unconfined compressive strength (UCS) of the treated samples was measured according to ASTM D2166-06 (ASTM 2006). The specimen was 30 mm in diameter and 80 mm in height, and the rate of vertical displacement was fixed at 1.5 mm/min until the failure of the specimen.

The permeability of the treated samples was determined using a triaxial cell. All the treated samples were first saturated at a back pressure of 100 kPa for 16 h. After that, an effective confining pressure of 50 kPa was applied by the pressure controller. A back pressure of 30 kPa was then applied to the base of the samples, while the upper drainage system was open. The coefficient of permeability was calculated by the change in volume recorded by the controller following Darcy's law. Based on the measured permeability coefficient, the porosity of sand column sample can be deduced through the formula. Through the change of porosity, the improvement of sample permeability by different treatment methods can be seen more directly.

The surface morphologies and microstructures of bio-treated sands were examined using a HITACHI S-4800 SEM apparatus (made in Japan). To minimize the disturbance to the microstructure of the sample, the freeze-drying method was used to dry the treated sample before the SEM analyses. The sample was then placed on an aluminum pedestal using silver Electrodag glue. It was fractured at mid-height, and stripped using epoxy resin. Finally, a high-vacuum ion plating machine was applied to spray gold on samples (Gitter et al., 2018).

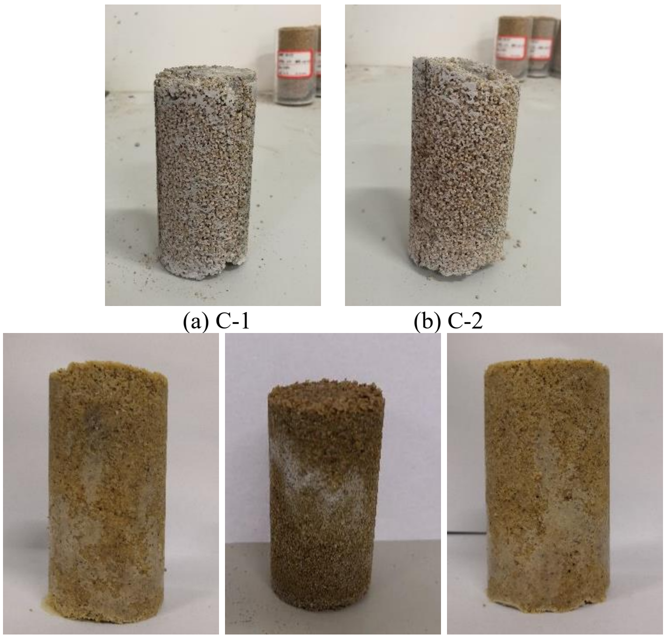
4. RESULTS AND DISCUSSION

4.1 Unconfined Compressive Strength

Figure 5 shows the reinforced specimen in this study. According to the characteristics of the reinforced sample, it is indicated that the pores between the sand particles of the sample after cement reinforcement were not filled fully, the gaps between the sand particles and fallen particles can still be observed clearly. For the samples reinforced by microbial grouting, the pores between sand particles were filled completely, and the microorganisms bond the loose sand samples into a stable whole.

Figure 6 shows the UCS of cement and microbial-reinforced sands and the number at the top of the bar chart represents the unconfined compressive strength of different samples. For *w/c* ratios of 2:1 and 4:1, the UCS of cement-treated samples C-1 and C-2 was 677 kPa and 312 kPa. Meanwhile, for microbial-treated samples, the maximum UCS is 3772 kPa, minimum UCS is 2796 kPa, and the average UCS is 3177 kPa, which is 4.69 times of C-1 sample (*w/c* = 2:1) and 10.18 times of C-2 sample (*w/c* = 4:1), respectively. This clearly shows that the UCS of biological treated sand is significantly higher than that of cement treated sand under the condition of seven days grouting test.

For further compare with other studies, the data M-a, M-b and M-c from Punnoi et al. (2021) are also illustrated in Figure 6. It is obvious that the UCS values in this study are higher 3-6 times than that of Punnoi et al. (2021). This may be caused by the soil used type. The soil used in the literature of Punnoi et al. (2021) is clay while the soil used in this study is sand.



(a) C-1 (b) C-2

(c) M-1 (d) M-2 (e) M-3

Figure 5 Reinforced sand samples

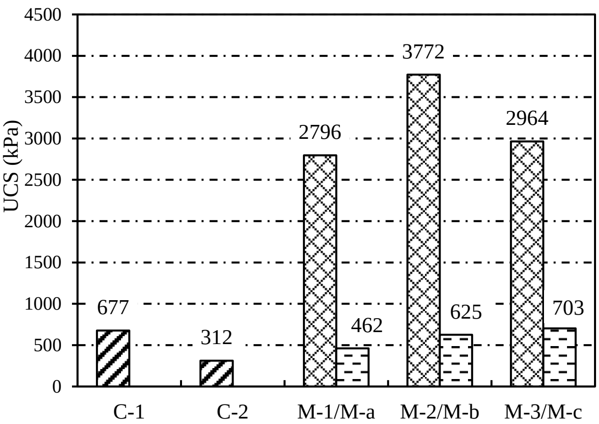


Figure 6 UCS of cement-treated and microbial-treated sands

4.2 Permeability Test

The permeability coefficient of treated samples was measured using a triaxial cell according to ASTM D2434-68 (ASTM 2006) in this study. An effective confining pressure of 50.0 kPa was applied to all samples. A back pressure of 30.0 kPa was then applied to the lower base of samples while the upper drainage system was left open. That is, the used hydraulic gradient i in the permeability test is 3.0/0.1 = 30. The permeability coefficient of reinforced samples can be calculated from the volume change following the Darcy's low (Bordier et al., 2000)

$$k = (\Delta Q \cdot H)/(60A \cdot 102 \cdot \Delta P \cdot \Delta t) \tag{1}$$

where ΔQ is the flow volume in Δt time (in cm^3); H is the height of samples after saturation (in cm); A is the average flowing section (in cm^2); ΔP is the pressure difference of flowing water (in kPa)，1 kPa pressure is equivalent to 102 mm water head difference; Δt is the flow duration (in s).

The change of sample permeability is reflected by permeability coefficient. Figure 7 shows the permeability of the cement-treated (C-1, C-2) and microbial-treated samples (M-1, M-2, M-3), pure sand was as the control group. It can be obtained from the calculation results: The permeability of cement-reinforced and bio-reinforced sands are much smaller than that of pure sand. The permeability of pure sand is approximately 5.6×10^{-3} cm/s. The permeability coefficient of C-1 Sample (w/c = 2:1) is 3.3×10^{-4} cm/s, which is an order of magnitude lower than that of pure sand, indicating that cement reinforcement has a positive effect on the permeability of sand sample. In particular, the permeability of C-2 samples (w/c = 4:1) changes little, this is because the cement w/c ratio is too large, as a result, the fluidity of cement increases, the cohesion decreases, and the gaps of the samples cannot be well filled. The average permeability coefficient of microbial-reinforced samples is 4.17×10^{-6} cm/s, compared with pure sand, it is reduced by three orders of magnitude, and it's only 0.05 times that of C-1 (w/c = 2:1), and it is only 0.0007 times that of the permeability of pure sand. The above data fully shows that microbial-reinforced sand has a more obvious reduction in permeability than cement-reinforced sand.

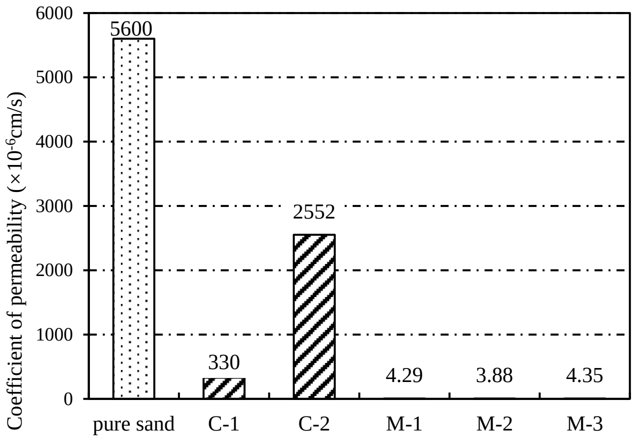


Figure 7 Permeability coefficients of pure and treated samples

For porous media such as sand, porosity can be used to reflect the cementation effect of different treatment methods on sand samples. The porosity of sand can be deduced and calculated by using the permeability coefficient through the following formula (Kozeny, 1927; Carman, 1939):

$$K = 0.083\frac{g}{v}\frac{n^3}{(1-n^2)}d^{10} \tag{2}$$

where g is the gravitational acceleration; v is the kinematic viscosity, which can be taken as 0.013 cm^2/s when the water temperature is 10 ^{o}C; n is the sand porosity, equals to be $e / (1+e)$; d_{10} is the effective particle size and the value is taken as 0.65 mm in this test.

Table 4 shows the change of sample porosity before and after cement and microbial treatment, which can reflect the filling amount of sample pore volume after curing, so the reinforcement effect of sample can be evaluated quantitatively: The average porosity of the sample after microbial reinforcement decreased by 12.83%, which was 1.2 times that of the C-1 sample (w/c = 2:1) and 3.7 times that of the C-2 sample (w/c = 4:1). It shows that the grouting effect of microbial reinforcement is better than that of cement reinforcement, the generated calcium carbonate crystals are more evenly distributed among the pores of sand samples, and can better bond the sand particles together. Particularly, although the decrease of porosity of C-1 sample is not much different from that of microbial-reinforced sample, the permeability coefficient is two orders of magnitude smaller, this is because although the cement slurry can block the pores between sand particles, the overall permeability of the strengthened sample is poor due to the non-uniformity of cement grouting and the poor impermeability of cement.

4.3 Interface Morphologies

In order to better explain the phenomenon of the enhancement of strength and the decrease of permeability of cement grouting sand and bio-grouting sand, the microstructure of grouting sand from the SEM analysis is shown in Figure 8. It can be seen from Figure 8(b) that different types of cementing agents created different kinds of bonding. Cement created lumps of hydrated and partially hydrated grains, while calcite generated by MICP formed granular depositions. In Figure 8(c), it seems that cement particles are more evenly distributed than calcite crystals. However, the cement lumps are more covered on the surface of sand particles, which makes it difficult to distinguish the sand particles and the cement. It also can be seen from Figure 8(d) that the cement-induced cementation is a bit more porous than the bio-cementation.

Table 4 Porosity values before and after treatment

Specimens	Cement-treated		Bio-treated		
	C-1	C-2	M-1	M-2	M-3
Water cement ratio *w/c*	2:1	4:1	-	-	-
Porosity values before treatment (%)	38.7	38.7	38.7	38.7	38.7
Porosity values after treatment (%)	28.2	35.2	25.9	25.1	26.6
Porosity reduction (%)	10.5	3.5	12.8	13.6	12.1

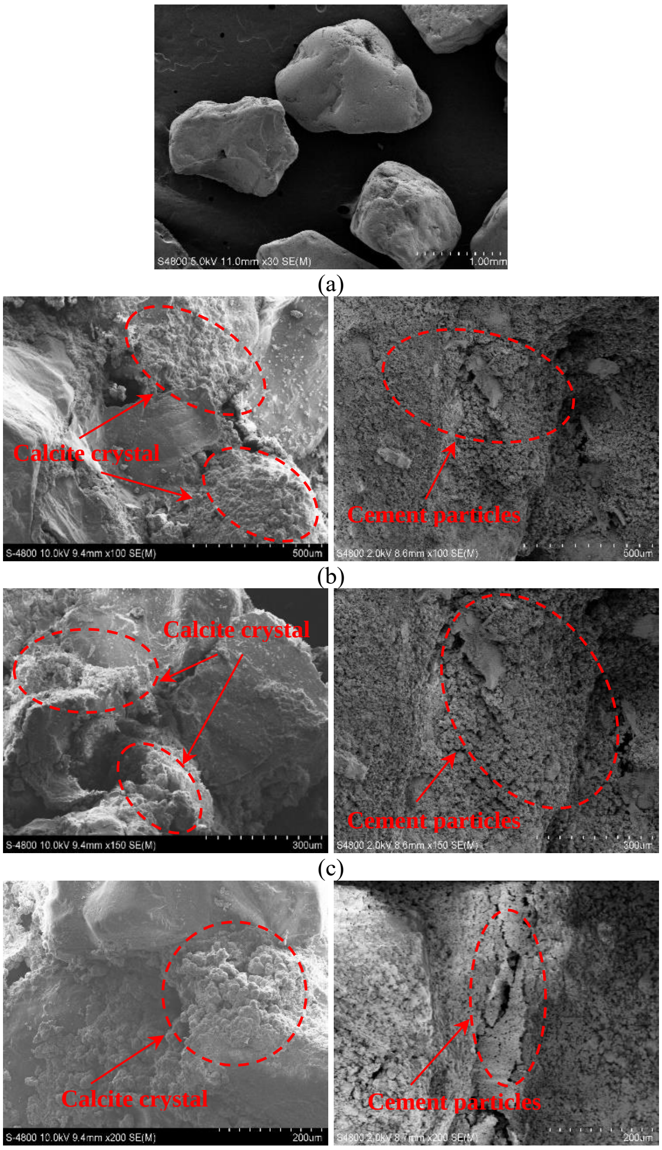


Figure 8 SEM image of bio-treated sand and cement-treated sand: (a) Siliceous sand particles, (b) 100 times magnification, (c) 150 times magnification, and (d) 200 times magnification

Further carefully observe the calcite crystals generated by MICP, the blocks with obvious edges and corners are the sand particles surrounded by cementitious products generated by biological reactions. For a treated sample with a magnification of 200 times in Figure 8(d), it is obvious that the sand particles are tightly wrapped up by the generated calcium carbonate precipitation. Moreover, calcium carbonate products not only cover the surface of individual sand particles, increase the volume of sand particles, form a dense calcium carbonate shell on the surface of sand particles, but also well connect the pores between sand particles, promote the formation of a connected whole between sand particles, so as to enhance the integrity of the sample and reduced the permeability of the sand sample. Therefore, it can be inferred that when the sand is reinforced by two methods in the same period of time, microbial-reinforced may create stronger bonding than cement, that is because the calcite produced by MICP can not only be widely attached to the surface of sand particles, but also better penetrate into the voids between sand particles, formed more effective ways of connection and make more effective bonding. This explains why microbial-cement sand has higher unconfined shear strength and lower permeability coefficient in previous tests.

5. CONCLUSIONS

This study is an investigation of the potential use of microbiology as a substitute for cement to stabilize sands. The main conclusions are summarized as follows:

1) For sand samples with particle size of 0.63-1.25, there is an optimal water cement ratio for cement grouting. High or low water cement ratio will lead to poor reinforcement effect. However, for microbial-grouting, the cell length is usually between 0.5 to 3.0 micrometers, which is much smaller than the particle size of cement slurry, the bio-slurry can travel through sand pores more smoothly. Compared with cement slurry, the bio-slurry has better flow ability and the generated calcite could be evenly distributed in the pores of sand particles.
2) For the specific 7-day grouting time, the curing time for cement grouting is short, and the strength of the sample didn't reach the highest. However, for microbial-reinforced sand, reached a certain strength faster and higher than the cement-reinforced. The UCS of the samples treated in two ways proves this. When the actual project requires rapid reinforcement of soil, microbial method shows better characteristics than cement grouting method in reinforcement speed and reinforcement strength.
3) Compared with microbial reinforced clay, MICP is more suitable for strengthening sandy soil. This is because the sand has more pores and better permeability, which provides more attachment points for microbial bacteria and calcite crystals. The more calcite generated means better improvement of soil strength.
4) The permeability test results indicate that the coefficient of permeability for the bio-reinforced sample is remarkably reduced, which is only 0.00068 times of pure sand. Moreover, it is only about 0.013 times the permeability of cement-treated sand. This indicates that a much higher cement content is necessary to achieve the same level of permeability. In this regard, the proposed bio-grouting method may lead to a substantial cost saving over the usage of cement.
5) By comparing the microstructure of cement-reinforced and microbial-reinforced samples. It can be concluded that, when the sand is reinforced by two methods in the same period. Microbial-reinforced would create stronger bonding than cement. The calcite produced by MICP can not only be widely attached to the surface of sand particles, but also better penetrate into the voids between sand particles, formed more effective ways of connection than cement particles. This explains why microbial-cement sand has higher unconfined shear strength and lower permeability coefficient.

6. ACKNOWLEDGMENTS

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