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State-of-the-art report soil improvement with bio-grouting materials

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In recent years, the cross-discipline of geotechnical engineering, microbiology and chemistry has shown good competitiveness in issues of modified soil. Microbial grouting material is a new type of modified soil material developed recently. By pouring bacterial liquid and nutrition into loose sand and using microbial mineralization to rapidly precipitate carbonate between sand particles, the physical and mechanical properties of soil are improved. This paper mainly summarizes the research of many scholars on the modified soil of biological grouting materials in recent years, and expounds the microbial-induced carbonate precipitation in biological grouting. The application and soil modification mechanism of three kinds of biological grouting materials: enzyme-induced carbonate precipitation and bio-induced carbonate dehydration and precipitation, and points out the great application prospect of biological grouting materials in geotechnical engineering and the problems to be solved in the future.

Keywords: biological grouting material, microbially induced $CaCO_3$ precipitation, soil improvement, bio cement.

Сучасний звіт про поліпшення грунту с біозатирочними матеріалами *Xiaolin Gu, Zixuan An, Ji Hongbo*

В останні роки міждисциплінарна геотехнічна інженерія, мікробіологія та хімія показали хорошу конкурентоспроможність у питаннях модифікованого грунту. Мікробний цементаційний матеріал — це новий тип модифікованого грунтового матеріалу, розробленого нещодавно. Фізико-механічні властивості грунту покращуються шляхом вливання бактеріальної рідини та поживних речовин у пухкий пісок і використання мікробної мінералізації для швидкого осадження карбонату між частинками піску. Ця стаття в основному підсумовує дослідження багатьох вчених щодо модифікованого грунту біологічних цементаційних матеріалів за останні роки та пояснює спричинене мікроорганізмами карбонатне осадження при біологічному цементуванні. Механізм застосування та модифікації грунту трьох типів біологічних цементаційних матеріалів: ферментно-індуковане карбонатне осадження та біоіндукована карбонатна дегідратація та осадження, а також вказує на великі перспективи застосування біологічних цементаційних матеріалів у геотехнічній інженерії та проблеми, які необхідно вирішити в майбутнє.

1. Introduction

With the continuous growth of the population and the acceleration of the urbanization process, the demand for important buildings is constantly increasing. It is inevitable to encounter some complex geological environment in the construction process, and the soil needs to be improved to meet the construction requirements. There are two kinds of soil improvement methods: physical and chemical, but the physical method has a specific limit to the improvement of soil properties, and the chemical method is most used in most construction processes. Because the reagents or materials used in chemical methods are artificially prepared, when injected underground to improve soil properties, they usually change the PH of the soil and may release toxicity, causing irreversible erosion and damage to local soil [1]. However, a new, green, and sustainable soil modification material is urgently needed to replace cement or chemical reagents in a large number of ground treatment projects around the world. Therefore, the process of modifying soil microstructure and engineering properties by microbial life activities and their metabolites has sound environmental and economic effects, which have been paid attention to by scholars at home and abroad.

Biological grouting materials is the use of the creatures that can grow in the porous medium (soil), activities, reproduction and reaction characteristics of soil were modified, sedimentary out employing biological induction have the gelling effect of calcium carbonate ($CaCO_3$) to fill the porosity of the soil, soil particle cementing and further enhance the strength of the soil and compactness of [2]. Previous studies have shown that the use of biological grouting materials can effectively reinforce soil [3, 4] and repair concrete cracks [5], which has the potential to be applied in geotechnical engineering and will bring a profound impact on the ecological environment and sustainable development of soil. At present, biological grouting materials mainly include Microbially induced $CaCO_3$ precipitation (MICP) [6]. Enzyme induced $CaCO_3$ precipitation (EICP) [7] and Microbially induced desaturation and precipitation (MIDP) [8]. Therefore, this paper introduces the theoretical basis of microbial modification, summarizes the application of biological grouting materials (MICP, EICP and MIDP) in soil modification, expounds on the mechanism of biological modification from the perspective of chemical, chemical and biological reactions, and points out the possible problems in the popularization and application of biological grouting materials. It provides the technical and theoretical basis for applying biological grouting materials in engineering.

2. Theoretical basis of microbial modification

Microbial modification is mainly the deposition of inorganic matter (biological mineralization: new calcium carbonate crystals or carbonates), deposition of inorganic matter (biofilm formation) and production of gases that partially deposit or cover pores and thus improve the soil. Table 1 presents a summary of various microbial mineralization mechanisms.

For practical purposes, nitrate reduction is accompanied by producing hydrogen sulfide, which is odorant and highly toxic. The effects of sulfate and iron reduction are not very rational, and large amounts of organic solvents are needed to obtain sufficient precipitation. Therefore, the method of calcium carbonate precipitation by urea hydrolysis is the best.

Urea bacteria are the most common bacteria for biological mineralization [21], which can be found everywhere in nature, mainly including Bacillus babble octococcus and Micrococcus urea, etc., and grow best at 25? and weak alkali environment [22], and have the most vigorous activity under the nutritional conditions of 31.16 g/L soybean meal and 11.18 g/L ammonium sulfate [23]. In addition, the primary forms of calcium carbonate produced by urea bacteria mineralization are calcite, vaterite, and amorphous form vaterite [24]. The study of Harkes et al. [25] showed that microbial mineralization positively affected permeability, stiffness, friction, and other soil properties. Hammes and Verstraete [26] proposed that the combination of extracellular alkaline pH and calcium ions makes the pressure difference inside and outside the cell. The passive intracellular transfer of Ca^{2+} due to complementary $Ca^{2+}/2H^+$ electrochemical gradients lead to intracellular Ca^{2+} accumulation and excess proton expulsion. Under such conditions, bacteria must reduce intracellular Ca^{2+} and replenish protons previously expelled to survive, and this active bacterial regulation provides a favourable environment for calcium carbonate deposition. Miao et al. [27] found that microbial effects on granular material properties mainly depends on the ability of microbial metabolism in the soil, and the amount of contact with the soil, soil microorganism and the geometry between clearance was a key factor limiting mineral deposits, the relative compactness of soil to some extent restrict the freedom of migration and life activities. Okwadha and Li [28] confirmed through X-ray diffraction, scanning electron microscopy and energy dispersive X-ray analysis that the sediment formed by microorganisms was $CaCO_3$. Moreover, the type of thallus, the concentration of bacterial cells, the initial urea concentration, the reaction temperature, the initial Ca^{2+} concentration and the pH value of the medium

Table 1. The table of various microbial mineralization mechanisms [9–20].

Types of technology	Strains/metabolite	Mechanism of action	Reaction equation
MICP	Urea hydrolysis	Bacillus babble octococcus (basophilic bacteria)	The thallus produces a large amount of highly active urease through metabolic activities
	denitrification	Denitrifying bacteria	NO_3^- is reacted by CH_3COO^- to generate CO_2 and N_2, while CO_2 meets water to form HCO_3^-, which is combined to form calcium carbonate crystal deposition under alkaline conditions
	Reduction by ferric iron	Iron salt reducing bacteria	The bacteria consume polysaccharides and monosaccharides through metabolism to produce organic acids and reduce trivalent compounds to produce soluble Fe^{2+}. Under the action of microorganisms, Fe^{3+} is formed, thus forming insoluble carbonate
	Myxococcus xanthus	Mucobacteria (Gram-negative bacteria)	NH_4^+ and CO_2 are generated by the metabolism of the bacteria, and the PH value in the soil increases. The continuous increase of PH value leads to the solubility of CO_3^{2-} ions
	sulfate reduction	Sulfate reducing bacteria (Anaerobic microorganisms)	Under the condition of anoxia and presence of organic matter, the thales reduce SO_4^{2-} after calcium sulfate dissolution to HS^- and generate HCO_3^-. Under alkaline conditions, Ca^{2+} and HCO_3 combine to form calcium carbonate deposition
EICP		Free urease	Similar to MICP, except that free urease replaces urea bacteria
MIDP	Microbial denitrification	Denitrifying bacteria	Nitrate, acetate, calcium, bacteria and nutrients are introduced into the soil to activate denitrifying bacteria, which dissimilar the nitrate and produce N_2 and calcium carbonate

were all the influencing factors of microbial modification. This is similar to the research results of Barabesi et al. [29], but they also believe that sediment structure is also related to environmental conditions. Li and Qu [30] studied the growth of the mineralized layer, the influence of deposited crystals on the pore of a substrate and the bonding effect of the mineralized layer and found that the Ca^{2+} source would affect the crystalline phase of calcium carbonate mineralized deposition. Bacteria could act as nucleation sites in this process to make crystals grow uniformly on the substrate surface.

3. Microbially induced calcium carbonate precipitation

3.1. Effect of MICP on mechanical properties of soil

MICP is the most common biological grouting material. It uses microorganisms as a natural resource to improve soil, an environmentally friendly soil improvement technology that has been widely used in geotechnical engineering and cement materials [31–34]. Whiffin [6] first proposed to induce calcium carbonate deposition in loose sand by using bacillus pasteurii and found that this method could significantly improve the shear strength of sand. A large number of research results show that MICP technology can effectively improve the soil's strength, improve the soil's permeability, and repair soil and concrete cracks [9]. Liu et al. [10] repaired dry cracks in a cohesive soil and found that MICP was conducive to enhancing the soil's dryness resistance and improving its mechanical properties when dealing with cohesive soil. The results of the large-scale test of 100 m^3 show that the MICP grouting can produce more than 28 % calcium carbonate deposition, make the unconfined compressive strength exceed 20 MPa, and increase the compression modulus by 100 times [3, 6, 13]. Chou et al. [35] and Bing [36] also reached a similar conclusion: with the increase in MICP grouting amount, the shear strength of the modified soil gradually increased, the cohesion also exceeded 5.5 KPa, and the friction Angle was greater than 43°. The MICP anti-permeability test found that the anti-permeability performance was better with the increase in grouting quantity and duration. The permeability coefficient of sand decreases to 10^{-7} m/s ~ $1.4 \cdot 10^{-4}$ m/s [37–39]. Lin et al. [40] found that the distribution forms of carbonate crystals in sand pores mainly include contact consolidation, particle coverage and matrix support and proposed that the permeability of sandstone after MICP treatment could be estimated by the Panda-Lake model. Martinez et al. [41] found that the overall hydraulic conductivity would gradually decrease with the increased calcium carbonate content in the soil. Peng et al. [42] found that the Darcy permeability coefficient of fractured rock after MICP modification was reduced to about $3–5 \times 10^{-5}$ m/s, which was four orders of magnitude smaller than that of unmodified fractured rock. Moreover, the MICP modification effect was closely related to fracture roughness, urea and calcium chloride concentration, and fracture pore size.

3.2. Permeability

The results show that calcite formed by microbial mineralization fills the pores of soil particles, reduces the porosity of the soil, and improves the permeability of the soil. Some scholars have pointed out that microbial mineralization reduces the permeability of the soil layer, which is helpful for oilfield development [43]. In another study, MICP was used to successfully construct a laboratory-scale pool model to form a cementable layer containing calcite on the soil surface. This resulted in a permeability reduction of three orders of magnitude [44]. Rong et al. [45] obtained consistent results in similar experiments. The porosity and XCT test results show that the porosity of sand after MICP modification is reduced by 34 %, and the grey value of CT is increased by 12 %. It can be concluded that MICP technology can effectively fill soil pores and improve soil permeability by using calcite deposition.

Different from the above, whiffin et al. [39] found that although microbial-induced calcite deposition could fill the soil pores, its improvement effect was not satisfactory. In the experiment of 5m sand grouting reinforcement, MICP technology improved the soil's strength, but the sand's porosity and permeability did not change significantly. After curing, the permeability coefficient decreased from $1.92 \cdot 10^{-5}$ m/s to $9.0 \cdot 10^{-6}$ m/s. Even the sand samples with the highest calcite deposition will have a porosity reduction of 10 %. Most of the pores are preserved. Shen [38] found that when the unconfined compressive strength of the solidified sand column reached 1.38 MPa, the calcite production only accounted for 14 % of the pore volume, indicating that there were still a large number of pores in the sand column and a significant permeability coefficient was maintained. Van et al. [46] found that the MICP-modified soil maintained high porosity and permeability. Therefore, only when the strength of MICP-modified soil exceeds the critical value, there is a critical value of MICP-modified oil, and the permeability of soil gradually decreases. This is mainly due to the problems of calcite formed by microbial mineralization, such as easy aggregation and uneven distribution. It is worth noting that since calcite tends to be deposited near the contact of sand particles, MICP modification can obtain higher strength and maintain pore connectivity and large permeability. These characteristics also enable microbial grouting to achieve low pressure, long distance, and multiple cycles of perfusion.

3.3. Freeze-thaw resistance

Using microbial cement, Rong et al. [47] successfully cemented a cylindrical sand column with a height of 50 cm and a diameter of 5 cm. By studying the compressive strength, freeze-thaw cycle and scour property of the sand column at different locations away from the injection port, it was found that the compressive strength of the microbial cement sand column decreased continuously as it was away from the injection port. The sand column at 0–30 cm distance from the injection port has good freezing resistance, while over 30 cm has poor freezing resistance. After 0.5 h scour, the different parts of the 50 cm high sand column cemented by microbial cement have good scour resistance. Cheng et al. [48] also compared and analyzed the freeze-thaw resistance of cement-solidified sand samples and MICP cemented sand bodies and found that after ten freeze-thaw cycles, the strength of cement-solidified sand samples decreased by 40 %.

In contrast, the strength of MICP cemented sand body only decreased by 10 %. Presently, researchers at home and abroad mainly focus on microbial consolidated sand bodies' mechanical properties (strength, stiffness, and permeability). However, relatively few studies have been conducted on their durability under conventional and complex environmental conditions, so it is necessary to further strengthen the research in this aspect.

3.4. Resistance to erosion

Gomez et al. [49] took the lead in conducting field test research on the resistance of the microbial cemented surface sand body to erosion damage. Bacterial liquid and cementing solution were used to consolidate the surface of loose tailing sand on site, and a hard cementing layer with a thickness of 2.5 cm was finally formed. Dynamic penetration and calcite content test showed that the adequate reinforcement depth reached 28 cm, which significantly improved the erosion resistance of loose mineral sand and created favorable conditions for vegetation restoration in the future. Jiang et al. [50] conducted seepage erosion tests on the mixed soil samples strengthened by microbial grouting (sand: kaolin = 5:1). The results showed that the soil's critical hydraulic gradient and shear stress significantly increased after the reinforcement. In contrast, the internal erosion under the same hydraulic conditions was significantly reduced. Bang et al. [51] found that evenly spraying bacterial solution and cementing solution on the surface of sandy soil can form a cementing thin layer with a certain hardness to effectively improve the wind erosion resistance of solidified soil.

3.5. Principle of microbial-induced calcium carbonate precipitation

Where urea hydrolysis mechanism is to use a pap bacillus with urea as energy through metabolism activity produces a large number of highly active urease, formed under the catalysis of urea hydrolysis and ammonium and CO_2, the distribution of cell wall to the system in the solution generated by hydrolysis of NH_4^+ and CO_3^{2-}, and calcium salt solution of pumping Ca^{2+} adsorption in bacteria cell wall surface. This is due to the microorganism cell wall surface with a large number of opposing ion groups caused by. Finally, microorganisms transport CO_3^{2-} to the cell surface and combine with Ca^{2+} to form calcium carbonate crystals through life activities. The complete chemical reaction process is shown as follows [52]:

$$CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3, \quad (1)$$

$$NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3, \quad (2)$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+, \quad (3)$$

$$2NH_3 + H_2O \leftrightarrow 2NH_4^+ + 2OH^-, \quad (4)$$

$$\begin{gathered} HCO_3^- + H^- + 2NH_4^+ + 2OH^- \leftrightarrow \\ \leftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O \end{gathered}, \quad (5)$$

$$Ca^{2+} + Cell \rightarrow Cell\text{–}Ca^{2+} \quad (6)$$

$$Cell\text{–}Ca^{2}+ + CO_3^{2-} \rightarrow Cell\text{–}CaCO_3^-, \quad (7)$$

Finally,

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3. \quad (8)$$

In the process of soil modification by MICP, bacillus pasteurii plays two main roles: on the one hand, it provides high activity urease for urea hydrolysis; On the other hand, individuals with tiny thalli offer nucleation points to calcium carbonate deposition [11]. For the carbonate formed, it can not only fill the pores between soil particles but also increase the density and friction coefficient between soil particles. In addition, the carbonate crystal also has the cementation effect, which increases the cohesion between soil particles and makes them closely connected to form dense blocks, thus modifying soil. In addition, Qian et al. [53, 54] analyzed the electronic binding energies of C–O bonds in carbonate crystals and Si–O bonds in gravel produced by MICP modification through modern testing techniques. The results show that the hydrogen bond between carbonate crystals and sand and gravel is formed under the action of microorganisms, and the loose soil particles are cemented to form a whole.

3.6. Application status of MICP for soil reinforcement

The current research has confirmed that MICP can improve various practical problems of geotechnical engineering in granular soil, as shown in Table 2. Laboratory and local engineering have proved that

Table 2. Laboratory test studies of sand soils improvement by bio-grouting method

Test type	Test details	Effectiveness	Ref.
Sand-base	The size of the sand base is 8×5.6×2.5 m, and the density of fine sand is 1.56 g/m^3. The bacterial and cementation solutions were successfully injected from the perfusion well and perfused for 12 days	The calcite deposition content formed by microbial mineralization reached 110 kg/m^3, and the unconfined compressive strength of the sandy soil was 0.7 ~ 12.4 MPa	[55]
	The size of the sand-base is 0.9×1.1×1.0 m. Fine sand injects 100 L of bacterial solution and 4000 L of cementing solution	The sediment content of calcite formed by microbial mineralization reaches 100 kg/m^3, the static tip resistance of the shallow cone is as high as 5 MPa, and the maximum uniaxial compressive strength of the sand sample is about 9 MPa.	[56]
	The sand-base size is 1.12*0.96*0.95 m. River sand is used, and the average particle size is 0.25 mm. The bacterial solution, $CaCl_2$ solution and cementation solution are recirculated in stages	The sediment content of calcite formed by microbial mineralization is about 2 % ~ 9 % and the unconfined compressive strength of sand samples is 10 ~ 1 400 kPa	
Sand pile	The height of the sand pile is 5.0 m, the inner diameter is 66 mm, and the sand is fine. The bacteria solution, $CaCl_2$ solution (fixed solution) and cementing solution were injected with a peristaltic pump for 124 hours	The average calcite production is 59 kg/m^3. Under the confining pressure of 50 kPa, the consolidation drainage strength of the sand sample is 200 ~ 570 KPa. The permeability of sand samples was reduced by 22 % ~ 75 %	[39]
	The height of the sand pile is 50 mm the diameter is 5 mm, the Ottawa sand, the median particle size is 0.21 mm; The bacterial solution and cementing solution were injected from the top and bottom of the sand pile in turn, and the grouting was strengthened for 50 h	The yield of calcite is 50–98 kg/m^3. The shear wave velocity of sand samples ranges from 600 to 1100 m/s	[57]
	The sand pile has a height of 144 mm and a diameter of 72 mm. The median particle size of Ottawa sand is 0.21 mm. The bacterial and cementing solutions were successfully injected from the bottom of the sample for 28 h	Under confining pressure of 100 kPa the undrained shear strength increases about four times	[1]

MICP has a good modification effect on soil, and MICP has been applied to practical engineering, as shown in Table 3. However, before the large-scale application of MICP technology, the challenges to be solved mainly include economic cost, ecological environment, uniformity of MICP injection, and complex soil characteristics.

4. Enzyme-induced calcium carbonate precipitation

EICP technology has advantages over MICP technology because the enzyme has high activity even when microorganisms cannot grow, there is no oxygen supply problem, it is more effective for soil improvement, and it is suitable for more stringent soil conditions. Javadi et al. [62] found that the extracted urease activity was 611 U/mL, and the precipitation amount of calcium carbonate reached 64 % of the theoretical value. Chandra and Ravi [63] modified three different types of soil with calcium carbonate precipitation catalyzed by urease from crops, and the test results showed that EICP technology could effectively improve the unconfined compressive strength of the soil. Almajed et al. [7] studied the combination of EICP and cement for soil improvement and found that EICP biological cementing technology can be effectively used alone without mixing cement, and the unconfined compressive strength of sand treated with EICP is higher than that of Portland cement with 10 %. Wu et al. [4] found in the test of solidified sand that the compressive strength of solidified samples was positively correlated with calcium carbonate content. With the increase of sand particle size, the compressive strength of sand first increased and then decreased.

Table 3. MICP engineering application

Years	Location/project	Specific application measures	Effect	Ref
2011	Netherlands	The treatment of sand and gravel foundation is about 1000 m^3, and the depth is 3 m ~ 20 m. Using circular grouting, 200 m^3 of diluted urea hydrolytic bacteria and 300–600 m^3 of urea and calcium chloride mixed solution were injected into the foundation.	The calcium carbonate content in the gravel soil is more than 6 %, and the maximum shear strength is more than 32 KPa. The gas pipeline foundation has good stability and anti-liquefaction performance	[58, 59]
2013	Underground garage in a community in Jinan	The soil near the wall with water crack was injected with a solution of bacillus pasteurii and nutrient salts	The soil becomes more uniform and compact when facing the water surface. The walls' cracks have been covered with a large amount of calcium carbonate, and the cracks have no rain seepage	[60]
2014	Alabama, United States	Reduce wellbore permeability and reduce CO_2 erosion	Wellbore water absorption is greatly reduced	[61]

This study shows that the application of EICP technology has specific requirements on soil particle size. Miao et al. [64] explored the use of EICP technology to improve the stability of the sand surface, and EICP technology can efficiently produce calcium carbonate precipitation between 10? and 70?. At the same time, the solidification strength of EICP + PAM (polyacrylamide) is 6.0–7.0 % higher than that of EICP alone. This method can make the sand obtain higher resistance to solid wind erosion. Liu et al. [65] compared the effects of EICP technology and MICP technology on the erosion resistance of coastal dunes and found that both methods could not effectively improve the erosion resistance of dunes, but the calcium carbonate precipitation using EICP was more uniform than MICP. Dakhane et al. [66] found that plant urease was used to repair concrete cracks, and the study showed that the flexural strength and fracture toughness of treated mortar increased by 33 % and doubled, respectively. It is found that the flexural strength and fracture toughness of mortar is directly proportional to the precipitation amount of calcium carbonate. The mechanism of soil modification by EICP is similar to MICP, which is based on calcium carbonate precipitation induced by urea hydrolysis. The difference is that EICP uses urease instead of bacillus pasteurii. Urease is soluble in water, and its nanoscale size allows it to penetrate all kinds of soils, including silty soils, and it is protected from the fungal activity and the transport of organic solutions. It also has a good advantage for modifying deep soil, and urease can provide nutrients for the metabolism of fungi or other microorganisms.

5. Microbial induced dehydration and carbonate precipitation

MIDP uses microbial denitrification to produce gas and precipitate calcium carbonate. The process is analyzed in two stages. In the first stage, dehydration slows soil liquefaction down in the short term. In the second stage, the soil was modified by carbonate deposition. Rebate-Landa and Santamarina [67] found that soil with different acceptable powder content could be dehydrated through microbial denitrification, and the gas produced in the soil after MIDP modification would increase with the increase of permissible powder content (specific surface area). The gas distribution and stability after MIDP modification mainly depend on the soil's pressure condition and particle size distribution. He et al. [68] found in the test that denitrification could make the degree of dehydration of sand and gravel soil reach 80 % ~ 95 %, and the volume strain, pore pressure and settlement all decreased significantly. The above results are mainly at-tributed to introducing nitrate, acetate and other solutions and bacteria into the soil in MIDP to promote the dissimilar reduction of nitrate by denitrifying bacteria in the soil and the gradual formation of carbonate deposition when N_2 is produced. This process controls the amount and rate of N_2 production by adjusting temperature and the rate at which organic nutrients are injected. Meanwhile, the precipitation rate of MIDP modified denitrification carbonate was slow, resulting in larger calcite crystals formed by deposition. At the same time, the defoaming of gas and the interaction between users and residue made the carbonate deposition mainly concentrated in the soil particles. Currently, in terms of engineering applications, MIDP and MICP face the same problem, which is the high economic cost of organic nutrients and raw materials for calcium sources needed to promote denitrifying bacteria and how to achieve efficient distribution. If the economic cost can be effectively reduced, MIDP will be an effective measure for soil modification.

6. Conclusions and prospects

In conclusion, biological grouting material is a sustainable and green soil modification. Under the effect of microbial mineralization, bio grout materials can produce carbonate to effectively consolidate soil, which can not only fill the gaps between soil particles, increase the density and friction coefficient of soil, but also close cracks or reinforce soil. Biological grouting materials have the characteristics of less energy consumption, less pollution and good performance, and have great application potential in various cracks repair and soil reinforcement. However, there are still many problems in the promotion and engineering application of biological grouting materials at present, and the bottleneck to be broken through in future research mainly includes the following points:

The research on soil modification by biological grouting is still in the experimental stage, and the engineering technology is not mature enough. In the grouting process, how to avoid the uneven distribution of microorganisms caused by biological grout material. Through developing large-scale biological grouting samples to simulate the field environment and continue accumulating relevant experience to optimize and improve the relevant technology research.

Mineralization deposition based on urea hydrolysis is a hot topic in biological grouting research. However, a high concentration of ammonium chloride will also be produced when MIDP modified soil, which will seriously pollute groundwater and the soil environment. Similar problems are also encountered in the process of MIDP modification. The treatment of the by-products after biological grouting will inevitably increase the economic cost of soil modification. Therefore, optimizing the economic cost is the content that needs further study in the practical application process.

Microbial grouting to reinforce soil involves a series of biochemical reaction processes. Therefore, when using geotechnical engineering finite elements or for the analysis and calculation of grouting effects, it is necessary to combine biochemical reactions with hydraulic transport and mechanical models and to establish new intrinsic relationships based on the stress-strain characteristics of MICP-cursed soil. Many issues of current bio-grouting models are not sufficiently considered, especially microbial growth, adsorption-desorption, and enzymatic processes, resulting in models that wrongly and ccurately respond to the distribution of calcite in the soil and the mechanical properties of the cured sand body. Therefore, it is necessary to further study and improve the microbial grouting model by combining in situ monitoring data.

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