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REVIEW

Recent development in biogeotechnology and its engineering applications

Hanjiang LAI[a,b], Shifan WU[b], Mingjuan CUI[b,c], Jian CHU[b*]

[a] *Zijin School of Geology and Mining, Fuzhou University, Fuzhou 350108, China*
[b] *School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore*
[c] *College of Civil Engineering, Fuzhou University, Fuzhou 350108, China*
[*] *Corresponding author. E-mail: cjchu@ntu.edu.sg*

ABSTRACT Microbial geotechnology or biogeotechnology is a new branch of geotechnical engineering. It involves the use of microbiology for traditional geotechnical applications. Many new innovative soil improvement methods have been developed in recent years based on this approach. A proper understanding of the various approaches and the performances of different methods can help researchers and engineers to develop the most appropriate geotechnical solutions. At present, most of the methods can be categorized into three major types, biocementation, bioclogging, and biogas desaturation. Similarities and differences of different approaches and their potential applications are reviewed. Factors affecting the different processes are also discussed. Examples of up-scaled model tests and pilot trials are presented to show the emerging applications. The challenges and problems of biogeotechnology are also discussed.

KEYWORDS biogeotechnology, biocementation, bioclogging, biogas, strength enhancement, liquefaction mitigation, seepage control

1 Introduction

Microorganisms play an important role in the formation of soils and rocks. The activities of microorganisms can influence the compositions and engineering properties of the soil or rock. Unfortunately, they have been usually underestimated in the geotechnical engineering practices due to the lack of understanding of these activities and their influences. A proper understanding of biological principles would lead to improved soil characterization, enhanced understanding of soil behavior, and even alternative geotechnical engineering solutions [1]. Realizing the potential of integrating microbiological concepts with geotechnical practice is essential for advancing the state of knowledge in geotechnical engineering. A considerable amount of efforts have been made in the past decades on this emerging interdisciplinary research. The National Research Council [2] identified the application of biological processes in geotechnical engineering as one of the priority research areas in the new millennium. The use of microbial activities to improve soil properties provides a potential opportunity for sustainable development in geotechnical engineering [3].

In this paper, an emerging branch of geotechnical engineering—Biogeotechnology [4], is introduced. Biogeotechnology deals with the applications of biological methods to geotechnical engineering problems. Some microbial processes can change the engineering properties of soils and thus be potentially adopted in geotechnical engineering practices. To date, most research projects in this area focus mainly on the applications of biocementation, bioclogging, and biogas generation for the improvement of engineering behavior of soil or rock joints [5–9], seepage control in soil or joined rock [10,11] and soil liquefaction mitigation [12,13], etc. These microbial methods, and their potential applications and influence factors, are reviewed in this study. Examples of up-scaled model tests and pilot trials are also presented to show the efforts of pushing this innovative technique forward. The challenges for the application of biogeotechnology are also discussed in this paper.

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2 Biogeotechnology

2.1 Biocementation

Biocementation is to precipitate inorganic substances to form relatively stable and strong bindings by microbial activity, such as oxidation, reduction, dissolution, and precipitation. This phenomenon is widespread in nature with various microorganisms, such as fungi, actinomycetes, or bacteria. One of the most studied microbial-induced cementation processes in recent years is the Microbially Induced Carbonate Precipitation (MICP), which involves different processes, including urea hydrolysis [14], denitrification [15], sulfate reduction [16], and iron reduction [17,18]. Some alternative bonding substances for performing MICP are also reported, such as the barium hydrogen phosphate by microbial deposition [19]. Among them, the urea hydrolysis process is considered the most effective in MICP treatment. Urea hydrolysis is catalyzed by urease-producing bacteria (UPB) to produce ammonia and carbonic acid, as shown in Eq. (1). The released ammonia consequently increases the pH value, as displayed in Eq. (2). As the pH increases, the carbonic acid converts into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, as reported in Eq. (3). In the presence of free calcium ions (Ca^{2+}), as expressed in Eq. (4), the calcium carbonate ($CaCO_3$) would be precipitated [20–22] based on the nucleation sites served by the bacterial cells [14,23–26].

$$CO(NH_2)_2 + 2H_2O \overset{\text{Bacteria}}{\rightarrow} 2NH_3 + H_2CO_3 \tag{1}$$

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH^- \tag{2}$$

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+ \tag{3}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \tag{4}$$

Bacillus pasteurii (American Type Culture Collection 6453), has recently been reclassified as Sporosarcina pasteurii (ATCC 11859), an alkalophilic bacterium with a highly active urease enzyme, which is the most used UPB in laboratory studies for the MICP. Some other microorganisms, such as Myxococcus xanthus [27], Thraustochytrium striatum [28], Escherichia coli HB101 [29], Bacillus sphaericus [30], and Sarcina ureae [31], also have been applied for the MICP treatment. The UPB also can be enriched or isolated from the local soil [25,32–43], groundwater [44] or waste-activated sludge [45,46], or in situ stimulated the natural indigenous bacteria [47–56].

Biocementation, utilizing the precipitated calcium carbonate with cementation through the MICP process, could bond the loose soil particles together as a whole and thus alter the engineering properties of soils. The biocementation has a great potential for the geotechnical applications related to strength enhancement, such as ground improvement [5,57–61], soil erosion mitigation [62–69], sediment stability [70], and dust suppression [71–75], etc. Besides, biocementation also can be applied for concrete crack remediation [76–78], historical building restoration [43,79], and ornamental stone protection [80–84], etc. However, it is worth mentioning that the durability of calcium carbonate may be influenced by some environmental factors, such as acid rain and freeze–thaw cycles [85,86].

2.2 Bioclogging

Bioclogging is the clogging of pore space in porous media by the microbial biomass [10], resulting in reducing its hydraulic conductivity. The microbial biomass could be the bacterial cells and their productions, such as the biofilms (composed of approximately 80%–85% extracellular polymeric substance) [11,87–89], and the precipitated calcium carbonate with MICP process shown in Eqs. (1)–(4). Besides, the nutrient that feeds the bacteria also can clog the pores [89]. For soil improvement, one major limitation or concern for the application of bioclogging in situ is the stability of the microbial biomass in soil [4]. It is known that both the bacterial cells, biofilm and the nutrient in the soil can be degraded, leading to the weakening or even failure of bioclogging effect [90]. By contrast, the stability or durability of the calcium carbonate in the soil is much better [90,91].

Bioclogging, based on the calcium carbonate precipitation with MICP process, could block the pores to reduce or avoid the seepage or isolate the material from contact with air. Thus, the bioclogging has a great potential applied in engineering practices related to the seepage control and materials protection, such as preventing the internal erosion of earth dams and levees [63,92,93], construction of aquaculture pond [74,94,95], sealing rock joints [96–100], CO_2 geological sequestration [23], corrosion protection of cement-based materials [101], enhancing the recovery of oil from oil reservoirs or controlling the flow of a spilled contaminant in a reservoir [102–104], etc.

2.3 Biogas

Biogas generally refers to the biogenic gases produced by the breakdown of organic or inorganic matter through microbial processes, such as the anaerobic digestion with anaerobic bacteria or fermentation with biodegradable materials. The most common biogenic gases found in subsurface soils are methane (CH_4), carbon dioxide (CO_2), hydrogen (H_2), and nitrogen (N_2). Among these gases, nitrogen has shown several advantages over other gases, including 1) not a greenhouse gas, 2) neither explosive nor corrosive, 3) very low solubility in water, and 4) an inert gas that does not react with other gases or chemicals in the soil. Thus, nitrogen gas presents a great potential to serve the ground improvement purpose. Denitrification, a microbially facilitated process of nitrate reduction, is the most studied microbial process to produce nitrogen in recent years. As shown in Eqs. (5)–(8), denitrification is a multistep bacterial metabolism involving several enzymes that catalyze the stepwise reduction of nitrate to nitrogen [105,106].

$$\frac{1}{2}NO^-_{3(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \xrightarrow{\text{nitrate reductase}} \frac{1}{2}NO^-_{2(aq)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \tag{5}$$

$$NO^-_{2(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{9}{8}H^+_{(aq)} \xrightarrow{\text{nitrate reductase}} NO_{(aq)} + \frac{3}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \tag{6}$$

$$NO_{(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \xrightarrow{\text{nitric oxide reductase}} \frac{1}{2}N_2O_{(aq)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \tag{7}$$

$$\frac{1}{2}N_2O_{(aq)} + \frac{1}{8}CH_3COO^-_{(aq)} + \frac{1}{8}H^+_{(aq)} \xrightarrow{\text{nitrous oxide reductase}} \frac{1}{2}N_{2(g)} + \frac{1}{4}H_2O_{(l)} + \frac{1}{4}CO_{2(aq)} \tag{8}$$

The complex reactions for denitrification can be simplified as follows:

$$NO^-_{3(aq)} + \frac{5}{8}CH_3COO^-_{(aq)} + \frac{3}{2}H^+_{(aq)} \rightarrow \frac{1}{2}N_{2(g)} + \frac{13}{8}H_2O_{(l)} + \frac{9}{8}CO_{2(aq)} + \frac{1}{8}HCO^-_{3(aq)} \tag{9}$$

Biogas, based on nitrogen production via the biological process of denitrification, is an effective way to desaturate the sand via introducing gas into it. Thus, the biogas has a great potential for the liquefaction mitigation of saturated sand [12,107,108]. The denitrifying bacteria can be isolated from various sources, such as wastewater, soils, and meadows. Most of them are heterotrophic bacteria, such as Paracoccus denitrificans and various pseudomonads [109,110]. Many researchers have adopted the enrichment culture method to cultivate denitrifying bacteria and applied them in the sand to generate nitrogen gas bubbles [12,13,15,111]. Similar to many other biological activities, denitrification is a high environment-interactive process. Environmental factors ineluctably affect the occurrence and effectiveness of the process. In general, complete denitrification is promoted by high soil moisture content, neutral to slightly alkali soil pH, high soil temperature, low rates of O_2 diffusion, and the presence of labile carbon source [112]. In dealing with the denitrification process, precautions should be taken as the concentration of nitrate, nitrite, and nutrient (electron donor) must be in a proper ratio [15]. Otherwise, undesired or even hazardous byproducts would accumulate and cause environmental contamination.

3 Strength enhancement of soil

Soils with poor engineering properties are often encountered in infrastructure constructions and must be improved to meet the requirements. Densification, replacement, geosynthetic or/and pile reinforcement, and cement or chemical grouting are the common soil improvement technologies. However, these approaches are usually energy-extensive consumption or not environmentally friendly. An alternative approach is to use the biogeotechnology of biocementation and bioclogging through the MICP process, which can become a low-cost, and environmentally friendly soil improvement technology. Numerous studies have demonstrated that the MICP process can significantly improve the engineering properties of soils, such as the strength [113–122] as shown in Fig. 1, stiffness [115,118,123–132], and thermal conductivity [133,134], etc. Some studies also proposed to further enhance the strength of bio-cemented soil by adding other materials, such as lime [42], fiber [54,125,135–143], hydrogel-assisted [144], the hydrophilic polymer [145,146], and alginate [147]. MICP based soil improvement involves a highly complex biological, physical and chemical process, which is mainly affected by the following four aspect factors: 1) soil properties, 2) urease producing bacteria (UPB) characteristics, 3) cementation solution (CS) parameters, and 4) treatment process. The effect of each is discussed in the following.

3.1 Effect of soil properties

I) Soil Type: To date, MICP treatment has been widely applied for different types of soils, including clay [52,53,148–150], silt [150,151], residual soil [42,129,152–155], coal ash [156,157], expansive soil [158], tabia [159], mixture of sand and clay [63,121,160–162] or silt [163–165], sandy soil [166,167], fine sand [85,168], coarse sand [85,168–173], calcareous sand [56,118,137,174–178], gravel [150,179,180] and

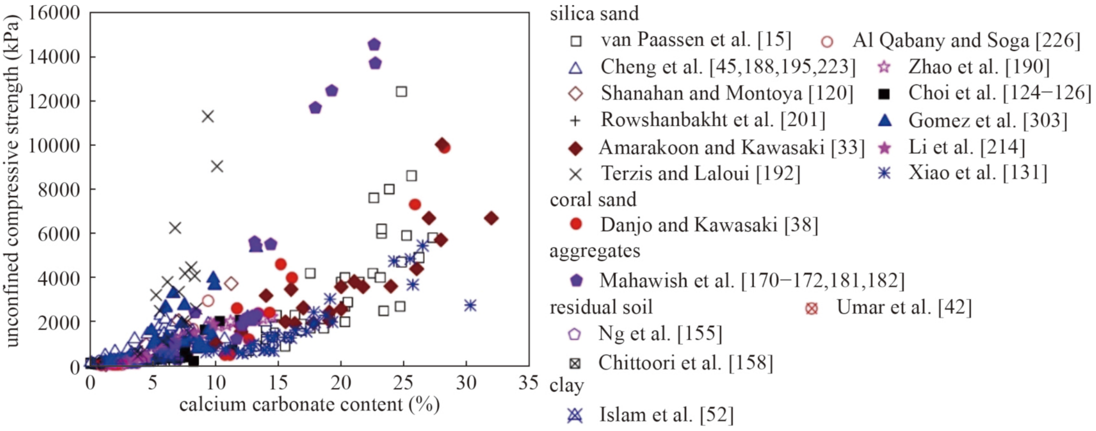

Fig. 1 Unconfined compressive strength of biocemented soil with calcium carbonate content.

aggregate [116,181–183], etc. Cardoso et al. [160] considered that the chemical interactions between the treatment solution and clay mineral must be considered when using MICP treatment for clay soil. On the contrary, Gomez and DeJong [184] claimed that the soil physical properties and calcite content were the two main governing factors on the soil improvement with MICP treatment, rather than the other biogeochemical differences. Soon et al. [154] also reported that MICP treatment was more effective in the strength enhancement of sandy silt than for the pure sand and attributed it to the insufficient interparticle contacts of sand caused by the contained coarser granular particles. However, Kim et al. [151] found that the MICP treatment was more active in the sand than in silt. So far, there is a lack of proper explanation at the fundamental level. More rigorous studies are required to establish the mechanisms behind it.

To date, most of the existing studies were carried out on soils with relatively coarse particles, although limited studies were reported for the use of MICP for fine-grained soils (e.g., clay). The major hindrance of using MICP to fine-grained soils is the geometric compatibility between soils and microbial communities. The soil with small particle sizes generally leads to a small pore-throat size. If the pore-throat sizes are comparable to or smaller than the sizes of bacterial cells, the bacterial cells would be retrained from penetrating the soil. Moreover, Phadnis and Santamarina [185] highlighted the importance of pore size for the viability of bacteria in soil, rather than the porosity. For instance, Rebata-Landa [150] found that the clay was uncemented due to the ignorable calcite content after 32 d of treatment. Kannan et al. [53] also reported that biostimulation is not effective in marine clay. Moreover, Sasaki and Kuwano [161] found that the improvement in liquefaction resistance was ignorable for the sand-clay mixture with MICP treatment and attributed it to the much small void ratio of the mixture causing the clogging of bacteria near the injection areas. However, Cardoso et al. [160] reported that the presence of clay minerals would increase the compressibility and reduce soil permeability, but do not significantly affect the MICP treatment. On the other hand, Ma et al. [186] also indicated that using a small amount of bentonite or kaolinite could help with the biocementation process for coarse sand.

For fine-grained soil with poor permeability (e.g., clay), the traditional MICP treatment with the percolation method is generally unsuitable. As an alternative, the mixing method has been widely adopted to apply MICP treatment with these types of soils [53,129,152,154,155]. Moreover, there are some novel applications of MICP treatment with fine-grained soils. For instance, Ivanov et al. [148] proposed to utilize the bio-encapsulation method to precipitate a calcite shell coated on the aggregates made of marine clay. Liu et al. [149] applied the MICP treatment to remidiate desiccation cracks in clayey soils. Islam et al. [52] proposed to utilize bio-stimulation to conduct the MICP treatment for clayey soil.

On the other hand, the MICP treatment may not be efficient for very coarse sand, gravel, and aggregate [150,173]. Rebata-Landa [150] reported that both the coarse sand and gravel were de-bonded with ignorable calcite content after 32 d of MICP treatment. Mahawish et al. [182] and Wu et al. [183] prepared well-bonded aggregates with a large amount of visible calcite cemented around the aggregates. Moreover, Pan et al. [173] and Wu and Chu [187] proposed to use the bioslurry [188] to improve the efficiency of MICP treatment for the soil with relatively larger particle sizes (e.g., aggregates, coarse sand). By using bioslurry, a unified grouting method has been proposed by Pan et al. [173] to be applied to the soil with a wide range of particle sizes.

II) Particle Size: Studies (e.g., Rebata-Landa [150], Pan et al. [173]) have shown that soils with too large or too small particle sizes are not conducive for the MICP treatment. For fine to medium coarse sand, the particle size may significantly affect the strength enhancement with the MICP treatment. Amarakoon and Kawasaki [33,189], Hoang et al. [168], Zhao et al. [190], Lin et al. [191], and Terzis and Laloui [192,193] reported that the strength enhancement of the bio-cemented soil was higher for relatively coarser soil under the same treatment conditions. Similarly, Jiang et al. [63] reported that bio-cementation of sand-clay mixture using coarse host sand was better than that with fine host sand. Amarakoon and Kawasaki [189] and Zhao et al. [190] attributed the effect of particle size on the bio-cementation to the soil permeability. The permeability would be greater for the soil with a larger particle size, which is beneficial for the treatment solution to be distributed into the soil, thus promoting the MICP process. Conversely, the soil with smaller particle sizes was more prone to clogging, preventing the penetration of treatment solution through the soil. Dhami et al. [194] also reported that the permeability reduction rate of the sand with large particle size was slower than that of small size during MICP treatment. On the other hand, Jiang et al. [63] considered that the inherent porosity would be greater for soil with larger particle size, which would host more carbonate precipitation.

On the contrary, Cheng et al. [85,195], Sharma and Ramkrishnan [121], Pan et al. [173], and Eryürük et al. [196] reported that the bio-cementation was more effective for the soil with small particle size. They considered that the soil with a smaller particle size could provide more interparticle contacts [85,121,173] and specific surface area [121] for the calcium carbonate precipitation and improve the homogeneity for the distribution of calcium carbonate [173].

III) Particle Gradation: In terms of the effect of particle gradation, Kim et al. [151] reported that the amount of the calcium carbonate precipitation in poorly-graded weathered soil was 5 times more than that of well-graded weathered soil and attributed it to the higher void ratio and greater void size in poorly-graded soil. On the contrary, Cardoso et al. [197] found that the soil with relatively good particle gradation has a large amount of calcium carbonate with the same treatment, but its unconfined compressive (UC) strength is relatively lower. On the other hand, Deng and Wang [175] reported that the UC strength of well-degraded soil is higher than that of poor-degraded soil with the same treatment. Cheng et al. [85] also found that the UC strength of well-graded sand was greater than that of uniform coarse sand while smaller than that of uniform fine sand and considered it might be related to the number of contact points. Moreover, Mahawish et al. [181], Gomez and DeJong [184], and Zamani et al. [198] reported that mixing a certain amount of fine-grain with a coarse grain soil could significantly improve the strength enhancement efficiency of MICP treatment. Mahawish et al. [181] attributed it to providing more contacts for calcium carbonate precipitation. Sasaki and Kuwano [161] considered that the presence of fine content might affect the morphology of the precipitated calcium carbonate.

IV) Soil Density or Relative Density (RD): Zamani and Montoya [165], Xiao et al. [176], Tsukamoto and Oda [199], Cheng et al. [200], Rowshanbakht et al. [201] and Lakshmi et al. [202] reported that a greater initial density or relative density (RD) generally leads to a higher strength of the bio-cemented soil with the same treatment or calcium carbonate content. Cheng et al. [200] and Rowshanbakht et al. [201] attributed it to the smaller spacing among particles with a greater initial density or RD, which is beneficial to form interparticle cementation. Soon et al. [154] also reported that the UC strength of the bio-cemented residual soil presented an increasing trend with its initial density but shown a reverse trend for the sand. They considered that both the denser residual soil and sand could provide more interparticle contacts, which is beneficial to improve the effectiveness of MICP treatment. However, the increase in density of sand would restrain the movements of bacteria and reagent solutions within the soil, and thus the MICP process would be retarded. Zamani and Montoya [165] found that more calcium carbonate would be obtained in soil with greater RD.

On the other hand, the studies of Kim et al. [151] and Mahawish et al. [170] implied that there is an optimum initial density or RD for the soil improvement with MICP treatment. Kim et al. [151] considered that the soil particles are not reasonably combined under either somewhat loose or dense conditions, resulting in less amount of calcium carbonate would be precipitated. However, Tsukamot and Oda [199] stated that the lower RD is beneficial to absorb more microbes and CS and thus precipitate more calcium carbonate. On the other hand, Mahawish et al. [170] claimed that more interparticle contacts with a greater RD are conducive to strength enhancement. Meanwhile, the size of the soil pore throat would be smaller with a greater RD, which in turn would result in the bacteria cannot infiltrate deeper into the soil, and as a result, a lower UC strength sample with heterogeneous distribution of $CaCO_3$ would be obtained.

V) Other Factors: Xiao et al. [131] and Song et al. [203] performed investigations on the effect of particle shape on bio-cementation. Song et al. [203] found that a greater amount and more homogeneous calcium carbonate would be precipitated with the spherical soil particles than angular particles. This is because the bacteria adhere more readily and forcefully to the smooth surface of spherical particles. On the other hand, Xiao et al. [131] reported that the UC strength of bio-cemented soil with angular particles is greater than that of rounded particles and considered this is due to the effective cementation area between angular particles is larger than that of rounded particles.

Cheng et al. [200] investigated the effect of initial pH of the soil on the soil improvement with MICP treatment and found that the soils under acidity and alkalinity conditions could precipitate more calcium carbonate than that of neutral soil, but their UC strength was lower than that of neutral soil. They considered this might be caused by the effect of pH value on the transport and adhesion of bacteria and the formation of calcium carbonate crystals.

3.2 Effect of UPB

I) Concentration (OD_{600}) of Bacteria: Amarakoon and Kawasaki [33], Liu et al. [66], Soon et al. [155], Zhao et al. [190], Eryürük et al. [196], Gat et al. [204], and Hataf and Baharifard [205] reported that the amount of the precipitated calcium carbonate and the bio-cemented soil strength tend to increase with the bacteria concentration (OD_{600}). Both Amarakoon and Kawasaki [33] and Zhao et al. [190] considered this because more bacteria could promote more enzymes and provide more nucleation sites for MICP. Wen et al. [206] reported that the increase in bacteria concentration could improve the precipitation rate of calcium carbonate, but the effect on the morphology of calcium carbonate was insignificant. Al-Thawadi and Cord-Ruwisch [32] reported that the size of the calcium carbonate crystal increased with the bacteria concentration. Wang et al. [207] found that a low bacterial density facilitated producing fewer crystals with larger average crystals volume. Zhao et al. [143,208] proposed to use the activated carbon and activated carbon-fiber felt to improve the bacterial retention ability and thus the yield of calcium carbonate. Moreover, Rowshanbakht et al. [201] reported that reducing the injected volume of bacteria solution to up to one-third of the pore volume did not significantly affect the performance improvement of the MICP treatment. On the other hand, percolating more bacterial cells into the soil may lead to clogging at the soil surface, resulting in the inhomogeneous distribution of the precipitated calcium carbonate [209].

II) Urease Activity (UA) of Bacteria: Zhao et al. [210] considered that using the bacteria solution with a higher UA could yield more calcium carbonate and, in turn, a greater UC strength for the bio-cemented soil. Achal et al. [211] proposed to cultivate new bacteria via UV irradiation to improve the urease activity of bacteria. However, Cheng et al. [85] reported that a lower UA of the bacteria generally led to a greater UC strength of the bio-cemented sand under the same calcium carbonate content and considered that a slower precipitation rate of calcium carbonate caused by a lower UA is more effective to bond sand grains.

3.3 Cementation solution parameters

Cementation solution (CS) is usually a mixture of calcium and urea. Some other substances may also be added to the CS in some studies, such as nutrient broth, NH_4Cl and $NaHCO_3$ [14,38,123,146,152,155,157,199,206,212–217], yeast extract [31,184], Tris base [31], sodium malate [38], sodium acetate [48,184], and polyvinyl alcohol [146]. Chen et al. [218] also proposed to use urine as the urea source for MICP treatment.

I) Calcium Source: $CaCl_2$ is the most commonly used calcium source for MICP treatment. Some researchers demonstrated that the efficiency in calcium carbonate precipitation [219,220] and strength enhancement [76] using $CaCl_2$ as the calcium source were higher than others, such as $Ca(NO_3)_2$, $Ca(CH_3COO)_2$, and $Ca(Ac)_2$. Abo-El-Enein et al. [76] attributed it to that more rhombohedral calcite could be precipitated using $CaCl_2$ as a calcium source, which is more conducive for the bonding among interparticle. However, Zhang et al. [221,222] reported that the UC strength of the bio-cemented sample using $CaCl_2$ was lower than that of $Ca(CH_3COO)_2$, while higher than that of $Ca(NO_3)_2$ under the same dry density.

Moreover, Cheng et al. [200,223] proposed to use seawater as the calcium source to prepare the CS by adding the urea into the seawater for MICP treatment. Some researchers [124,126,224] also proposed to dissolve the eggshell, limestone powder, oyster shell, and scallop shell, et al., by acid to provide the calcium source for MICP treatment. The MICP treatment is particularly suitable for calcareous sand, which contains a high percentage of calcium carbonate [225].

II) Concentration of Cementation Solution (CCS): To date, numerous studies have been conducted to investigate the effect of CCS on the biocementation of MICP. Cheng et al. [223], Al Qabany and Soga [226], Lai et al. [227], and Mujah et al. [228] reported that a lower CCS generally results in a greater strength enhancement of the biocemented sand under the similar calcite content. Both Al Qabany and Soga [226] and Mujah et al. [228] believed it was caused by the difference in the sizes of the precipitated calcite crystals. Al Qabany and Soga [226] found that the calcite crystals precipitated using high CCS had large size and inhomogeneity distributed spatially, which would cause the samples to deform locally during loading, resulting in smaller strength enhancement of the biocemented sample as a whole. Namely, the low strength enhancement of the biocemented sample using high CCS is due to the inhomogeneous cementation caused by the large size of the precipitated calcite crystals. Velpuri et al. [229] also considered that a higher CCS would lead to a more severe clogging at the injection point, and thus a more non-uniformly cemented specimen. Mori et al. [230] stated that low CCS could result in a more homogeneous pattern of calcite precipitation due to more nucleation sites than that of high CCS. Al-Thawadi and Cord-Ruwisch [32] also reported that the size of the crystal increased with the CCS. On the contrary, Mujah et al. [228] concluded that the sizes of the calcite crystals precipitated using low CCS were comparatively larger than that of high CCS and considered that larger crystals were more effective in enhancing the UC strength of soil. However, Lai et al. [227] considered that the effect of CCS on the biocementation of MICP might be mainly caused by the difference in bonding strength of precipitated calcium carbonate rather than other factors, such as calcium carbonate distribution.

On the other hand, Amarakoon and Kawasaki [33], Danjo and Kawasaki [38], Jiang and Soga [92], Wang and Tao [146], Lee et al. [152], Soon et al. [155], Deng and Wang [175], Zhao et al. [190], and Wen et al. [231] reported that the strength of the sample using high CCS was greater than that of low CCS under the same treatment conditions (e.g., number of treatments, total treatment duration), as more calcium carbonate would precipitate when using higher CCS. Meanwhile, Zhao et al. [190] stated that the increase rate for the UC strength of bio-cemented sand tends to decrease with the increase in CCS and attributed this to the process that the calcium cannot be fully utilized when the CCS is higher than 1.0 mol/L, which might be caused by the limitation of the enzyme quantities or the reduction in the urease activity of bacteria. Al Qabany and Soga [226] also reported that the chemical efficiency of the 1.0 mol/L case (about 20%) was much lower than that of 0.25 and 0.5 mol/L (varying from 70% to 100%) cases. However, they believed it was due to the less stable calcium carbonates (i.e., vaterite) would be precipitated using 1.0 mol/L and higher CCS, which may be flushed out at the subsequent injections. On the contrary, Li et al. [232] considered the lower CCS favored to form vaterite and the higher CCS favored to form calcite. Meanwhile, Li et al. [232] and Velpuri et al. [229] also claimed that the precipitation rate of calcite would increase with the calcium concentration (from 0.0125 to 0.1 mol/L). Okwadha and Li [233] suggested that the optimum MICP treatment were 666 mmol/L urea and 250 mmol/L calcium at 2.3E8 cells/mL bacterial cell concentration.

In terms of the upper limit of CCS for MICP, Lee et al. [152] and Soon et al. [155] found that shear strength and calcite content of the residual soil treated with 1.0 mol/L CCS were identical to those of the control specimen (supplied with cementation reagent without bacteria). They considered that, at high salinity (i.e., 1.0 mol/L), the bacterial activity would be inhibited and thus retarded the calcite precipitation. Al Qabany and Soga [226] also reported that most of the null UC strength samples were 1.0 mol/L samples. However, some other researchers [190,234–236] have claimed to obtain high-strength biocemented sand columns with CCS higher than 1.0 mol/L. For instance, Rong et al. [237] reported achieving a UC strength of 6.1 MPa for a sand column treated using a CCS of 2.0 mol/L.

III) Other Factors: Ghasemi et al. [238] performed an investigation on the effect of the ratio of calcium and urea on the bio-cementation and found that more treatments were required to reach the target cementation level if using the CS with a lower ratio of calcium and urea. Keykha et al. [239], Li et al. [240], Seifan et al. [241] reported that the treatment solution (containing bacteria, urea, and $CaCl_2$) with a higher pH (up to 12) is favored to yield more calcium carbonate.

3.4 Treatment process

I) Grouting technology: The grouting technology involves the parameters of a) grouting mode, b) grouting method, c) grouting rate, and d) grouting pressure.

a) Grouting mode: There are mainly three grouting modes: 1) Intermittent mode [85,242,243], 2) Continuous mode [242,243], and 3) Recycle mode [126,163,168]. The intermittent mode is conducted by injecting the treatment solution into the sample and then curing it for a period of time until the next treatment, the continuous mode is to inject the treatment solution into the sample continuously during the whole treatment duration, and the recycle mode is to inject a certain volume of treatment solution into the sample circularly. The intermittent mode is the most common grouting mode. Moreover, Martinez et al. [242] reported that the distribution of the precipitated calcite within 0.5 m sand column prepared with the intermittent grouting mode was more uniform than the continuous mode. Rong et al. [243] also reported that the UC strength of the sample prepared with intermittent mode was higher than that using continuous mode.

b) Grouting method: There are mainly three grouting methods: 1) Two-phase method [159,236,244–248], 2) One-phase method [26,132,234,249], and 3) Mixing method [152,154,155,190]. The two-phase method is a traditional grouting method done by: injecting the bacteria solution and the CS into soil separately with the percolation method. This method generally leads to uneven distribution of the bacteria attached in soil [250], thus distributing the precipitated calcium carbonate [243]. Moreover, a large amount of injected bacteria (more than 85%) was found to be flushed out of the sample during the injection of CS [247,208]. To assist the adsorption of bacteria in soil, Whiffin et al. [236] proposed injecting one pore volume of 50 mmol/L $CaCl_2$ solution into the sample immediately after injecting the bacteria solution. Harkes et al. [247] further improved this method by reducing the injected volume of bacterial solution to one-sixth of pore volume and increasing the injected volume of $CaCl_2$ solution to 1.5 times of pore volume. Cui et al. [246,251] proposed to use the two-step biological injection (i.e., injecting 0.4 pore volume of pure bacteria solution first and then injecting 0.6 pore volume of mixed bacteria solution) to improve the two-phase method. Zhao et al. [208] proposed to use the activated carbon to improve the bacterial retention ability.

The one-phase method is to inject the mixture of bacteria solution and CS into the soil at one time. In general, an instant and intensive ex-situ bio-flocculation would occur immediately after the mixing, leading to severe clogging at the injecting point. Kalantary and Kahani [249], Xiao et al. [132] proposed reducing the temperature of bacteria solution and CS to 3°C−4°C before the mixing, and Cheng et al. [234] proposed using a low pH bacteria solution ($pH \leqslant 6.0$) to prevent the clogging.

The mixing method introduces the bacteria into the soil by mixing the soil with a bacteria solution. This method is usually adopted for the soil with poor permeability, and the sample prepared with this method would be cured without repeated treatment [152,154,155] or immersed in a batch reactor filled with CS [157,160,190,206,212,231] until the pre-set curing time. The salt-solution fixing method injects the $CaCl_2$ solution into the soil immediately after the injection of bacteria solution to assist the adsorption of bacteria.

c) Grouting rate: Al Qabany et al. [252] reported that the chemical efficiency was maintaining at > 90% as the grouting rate of CS was lower than $0.042\ mol \cdot L^{-1} \cdot h^{-1}$ and would decrease to an average of 50% for a grouting rate of $0.084\ mol \cdot L^{-1} \cdot h^{-1}$. They considered that the difference in chemical efficiency with various grouting rates could be related to the bacteria-related process or experimental inconsistencies (e.g., variations in sand packing).

d) Grouting pressure: Most of the existing studies used granular materials with good permeability and thus generally used the grouting method without pressure (i.e., percolation method). The grouting with pressure is generally used for the soil with relatively poor permeability (e.g., residual soil). For instance, Soon et al. [155] adopt a pressure grouting method with a grouting pressure of up to 2 bar to inject the CS into the residual soil. However, when a high grouting pressure is used, the grouting can become a different category, such as fracture grouting rather than permeation grouting. For this reason, the injection pressure affects the results of biogrouting in the study reported by Lee et al. [129]. The UC strength of a residual soil treated using different injection pressures was affected by the injection pressure applied. The higher the pressure, the lower the UC strength, and the UC strength of the specimen treated using 0.2 bar injection pressure is 2.3 times higher than that using 2 bar. The permeability for the specimen treated under a 2 bar injection pressure is also 3.5 times higher, indicating the effect of possible fracture induced in the soil.

II) Number of Treatments or Cementation Level: It has been widely reported in the literature that the strength enhancement of the bio-cemented soil generally increases with the number of treatments [123,130,134,170,181,213,246] or the cementation level [115,117,131,244,248,253–256].

III) Treatment Duration or Interval: Several studies [33,42,121,123,130,155,190,202,239] have reported that the strength enhancement of the bio-cemented sample would be greater with longer treatment duration. On the contrary, Danjo and Kawasaki [38] found that the UC strength of the bio-cemented sample decreased with the increase of injection interval (0.5, 1, and 2 d), although the calcium concentration in the drainage with greater interval was lower than that of smaller interval. They considered that the calcites were more preferentially precipitated around the interparticle contact with smaller intervals. A similar result was also reported by Amarakoon and Kawasaki [33]. However, it should be noted that the UC strength is affected by other factors such as the uniformity of the treatment.

IV) Curing Temperature: Cheng et al. [200] and De Muynck et al. [83] reported that the sample curing at a higher temperature could produce more calcium carbonate, but its UC strength was smaller. Cheng et al. [200] claimed that the smaller UC strength at a higher temperature was due to the relatively smaller size of the precipitated calcite crystals that mainly cover the grain surface rather than fill the gaps between adjacent grains. On the other hand, De Muynck et al. [83] attributed it to the high precipitation rate of the calcium carbonate at a higher temperature, resulting in poor adherence and lower consolidative effect of the precipitated calcite.

On the contrary, Danjo and Kawasaki [38] reported that the UC strength of the bio-cemented sand increased by approximately 0.5 MPa with every 5°C increase in the curing temperature (20°C–35°C) and attributed it to more calcium carbonate would be precipitated at a higher temperature. Some studies also suggested that there is an optimal curing temperature for the soil improvement with MICP treatment. For instance, Mujah et al. [257], Cheng et al. [85] reported that the UC strength of the biocemented sand curing at 25°C was higher than that at 4°C and 50°C. Amarakoon and Kawasaki [33] found that the bio-cemented sand curing at 30°C had higher UC strength than that at 25°C and 35°C. Keykha et al. [239] suggested that 40°C was the optimum temperature for MICP treatment.

V) Saturation State during Curing: Cheng et al. [195] performed an investigation on the effect of saturation degrees of the sample during curing on the geotechnical properties of bio-cemented sand. Results showed that higher UC strength could be obtained for the bio-cemented soil with treatment under a lower saturation degree at similar calcium carbonate content. The microscopy images demonstrated that a strong coating effect of the MICP process was predominant for the sample at 20% saturation and the gaps between the host grains were almost filled with crystals. In comparison, for the sample at 100% saturation, the crystals precipitated not only at the interparticle contacts but also on the grain surface or suspended in the pore spaces. Cheng et al. [195] considered that, for a partially saturated condition, the MICP solution is predominantly concentrated at the interparticle contacts and thus the calcium carbonate precipitation, while in the case of full saturation, the MICP solution occupies the whole pore space and thus the calcite can be precipitated on both the grain surface and gain gaps. Shanahan and Montoya [120] also reported that the UC strength of the sample prepared with unsaturated treatment was greater than that with saturated treatment with similar calcite content.

VI) Oxygen Availability: Li et al. [214] studied the effect of oxygen supply on MICP treatment and reported that oxygen availability has a significant effect on the soil improvement with MICP process, and the UC strength of the sample curing with sufficient air supply could be 100 times that of air restricted. Seifan et al. [241] found that a higher aeration rate favored calcium carbonate precipitation. Jiang et al. [258] also reported that the ureolytic activity of B. megaterium in anoxic conditions was greater than that in oxic conditions. Mortensen et al. [259] considered that the MICP would not be diminished by the absence of oxygen or lysis of cells containing the urease enzyme on the time scale of an hour. The effect of oxygen depends on whether bacteria need to be cultivated in the soil. The function of oxygen is for the cultivation of bacteria, not the urologic process.

4 Seepage control of soil

Seepage control is a standard construction process for many infrastructure projects such as urban excavations, earth dams, tunnels, and other underground constructions. Excessive or uncontrolled seepage would impose a significant risk on the stability and safety of those constructions. The conventional countermeasure is to use cement or chemical grout to cope with the risk of undesired seepage and increase the work safety level. However, the particle size and viscosity of the cement and chemical grouting limit their application ranges. The effectiveness of standard seepage confinement is largely compromised when the soil pore size is extremely small. As an alternative, the bioclogging with MICP process has much lower viscosity than typical cement suspension, and it can flow like water inside the tiny pore in soil to induce calcium carbonate.

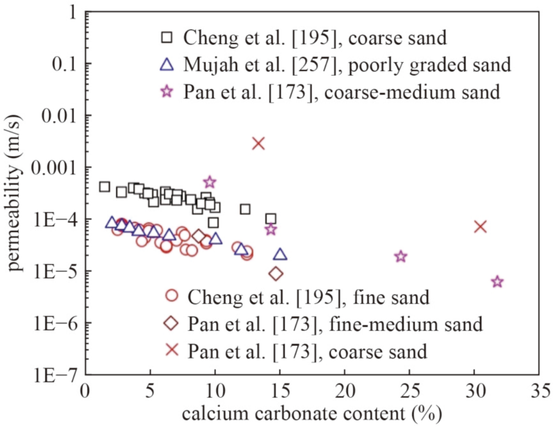

Fig. 2 Permeability of biocemented soil with calcium carbonate content.

As shown in Fig. 2, numerous studies have shown that the permeability of soils can be significantly reduced through the MICP process [4,35,46,108,127,224,250, 257,260–262] due to the pore-clogging caused by the precipitated calcium carbonate. In general, the permeability of biocemented soil depends on the initial pore-throat size of the soil and the amount of precipitated calcium carbonate. Several studies have implied that the reduction in permeability for the biocemented soil with greater density [205] or relative density [201,226], larger content of fine [163], smaller particle size [173,195,196], well-graded soil [175] are more significant with same treatment conditions due to the smaller pore space or pore-throat size in soil. Song et al. [203] also found that the permeability reduction for the soil with angular particles was greater than that with near-spherical particles and attributed it to the slot-shaped pores formed by the angular particles, which was more likely to be clogged by the precipitated calcium carbonate.

Moreover, the MICP treatment using a longer curing time [205,218], more number of treatments [37,40,74, 94,163,170,175,263], higher CS concentration [40,175, 205,223,231], greater bacterial density [205], or larger amount of injected bacteria [201] generally leads to a greater reduction in the permeability of the biocemented soil as more calcium carbonate would be precipitated with these conditions. On the other hand, Cheng et al. [85,195] found that, for the same amount of calcium carbonate, UA of bacteria has a minor impact on the permeability of biocemented soil [85], while a lower saturation condition could maintain a relatively high residual permeability [195]. Moreover, Pan et al. [173] and Yang et al. [264] proposed using bioslurry, a new type of biocement [188], for the seepage control of sand, which was proven to be more effective and efficient in the reduction of permeability. Cheng et al. [147] proposed a novel approach of using in situ microbially induced Ca^{2+}-alginate polymeric sealant for seepage control.

5 Liquefaction mitigation of soil

Saturated, loose, and cohesionless soils with insufficient cyclic shear strength have a greater potential for liquefaction when suffering cyclic loading, such as earthquakes, resulting in severe damage to engineering structures. Liquefiable soils are conventionally improved through dynamic compaction, chemical grouting, and deep mixing, which are typically energy-intensive and can negatively impact the environment. As an alternative, biogeotechnology presents promising approaches for liquefaction mitigation through improving soil's shear strength with biocementation or reducing the saturation degree of soil with biogas.

5.1 Soil strengthening with Biocementation

Several studies, conducted with the cyclic triaxial tests [48,161,176,177,265,266], centrifuge tests [255,267–269], cyclic direct simple shear test [270], and shake table test [178], have demonstrated that the liquefaction resistance of soil could be significantly enhanced through the MICP treatment, showing a reduction in the excess pore pressure (as shown in Fig. 3). Moreover, a higher cementation level for the biocemented soil generally leads to a greater enhancement of liquefaction resistance [48,176,177,255,268]. On the other hand, Montoya et al. [255] and Zhang et al. [178] found the surface accelerations were amplified for the biocemented soil, which is undesirable, and a trade-off between improving the liquefaction resistance and minimizing the surface acceleration should be considered for the design of cementation level.

Besides the cementation level, the distribution pattern of the calcium carbonate [265], saturation degree during curing [266], confining pressure [177], and fine content [161] were also reported to have effects on the liquefaction resistance of the biocemented soil. Feng and Montoya [265] found that the improvement of liquefaction resistance for the specimen with higher shear-wave velocity was more significant than that with lower shear-wave velocity under the same mass of calcium carbonate, and attributed it to the difference in the distribution pattern of the calcium carbonate. Simatupang and Okamura [266] reported that the lower the degree of saturation during curing, the greater the liquefaction resistance of the biocemented soil. This is due to the preferential precipitation of the calcium carbonate at the particle contacts under a lower saturation degree, which also has been reported by Cheng et al. [195]. In essence, it was caused by the difference in the distribution pattern of the calcium carbonate. Xiao et al. [177] found that an increase in confining pressure would lead to a decrease in the liquefaction resistance both for untreated and biotreated calcareous sand. Moreover, Sasaki and Kuwano [161] reported that the inclusion of fines would hinder the liquefaction resistance improvement of the biocemented soil and considered it was caused by the fines curtailing the efficiency of calcium carbonate precipitation at the interparticle contacts.

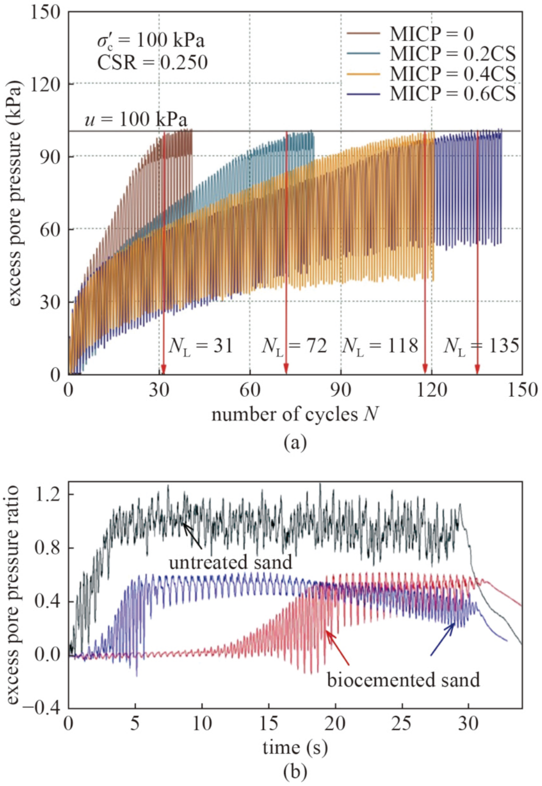

Fig. 3 Development of excess pore pressure for biocemented sand: (a) Cyclic triaxial tests of Xiao et al. [177] (Reprinted from Soil Dynamics and Earthquake Engineering, 107, Xiao P, Liu H, Xiao Y, Stuedlein A W, Evans T M, Liquefaction resistance of bio-cemented calcareous sand, 9–19, Copyright 2018, with permission from Elsevier); (b) shake table test of Zhang et al. [178] (Reprinted from Soil Dynamics and Earthquake Engineering, 129, Zhang X, Chen Y, Liu H, Zhang Z, Ding X, Performance evaluation of a MICP-treated calcareous sandy foundation using shake table tests, 105959, Copyright 2020, with permission from Elsevier).

5.2 Desaturation with Biogas

Studies [271–276] have shown that the mechanical behavior of soil is significantly affected by the presence of gas in either dissolved or free form. In particular, the liquefaction resistance of saturated sand can be largely enhanced by reducing its degree of saturation via introducing gas into it [274,277–282]. However, there is no effective way to inject gas bubbles uniformly into the soil and keep the bubbles in the soil for a long time. Meanwhile, the injection method is not a cost-effective approach. A biologically mediated process is a promising alternative for this purpose. The bacterial suspension could be easily introduced into the soil due to its low viscosity, leading to relatively uniformly distributed bacterial cells in the soil. Thus, the tiny gas bubbles generated in this way tend to be more uniform than that of injection method [12,275].

As shown in Fig. 4, a series of shaking table tests [12,107,110,283,284], cyclic triaxial tests [13,111,285–287], and centrifuge model test [288] have demonstrated that the bio-desaturation method, introducing the nitrogen into the sand with denitrification process, can significantly reduce the excess pore water pressure, mitigating the liquefaction potential of sand. He et al. [12] reported that the pore water pressure ratios could be smaller than 0.5 when the saturation degree of sand was lower than 95%. Meanwhile, a lower saturation degree of sand generally leads to a greater reduction in pore water pressure ratio, and the saturation degree could be controlled by the initial nitrate concentration added to the soil [12,107]. On the other hand, Rebata-Landa and Santamarina [275] considered that the soil grain size affects the entrapment of biogas in soil. The sand with a small percentage of fines may fail to trap the generated bubbles. To preserve the biogas in the sand, Wu [284] developed a method to combine the bio-desaturation (denitrification process) and bioclogging (MICP process) for mitigation of soil liquefaction through microbial processes. Flow tests for sand columns treated using the combined bio-desaturation and bioclogging method under a hydraulic gradient of 0.1 with either upward or downward flow indicate that the combined method effectively enhances the stability of the bubbles. Other studies performed by O'Donnell et al. [13,105,106,111], Wang et al. [276], Kavazanjian and O'Donnell [285], and Hall et al. [288] employed the denitrification process to induce calcium carbonate precipitation and generate nitrogen gas at the same time. The advantage of this process is that it provides an additional benefit for mitigating soil liquefaction through biogas (N_2) desaturation besides associated carbonate precipitation. The disadvantage is that the calcium carbonate precipitation induced via denitrification process is not as efficient as the precipitation caused by ureolytic bacteria [286,289].

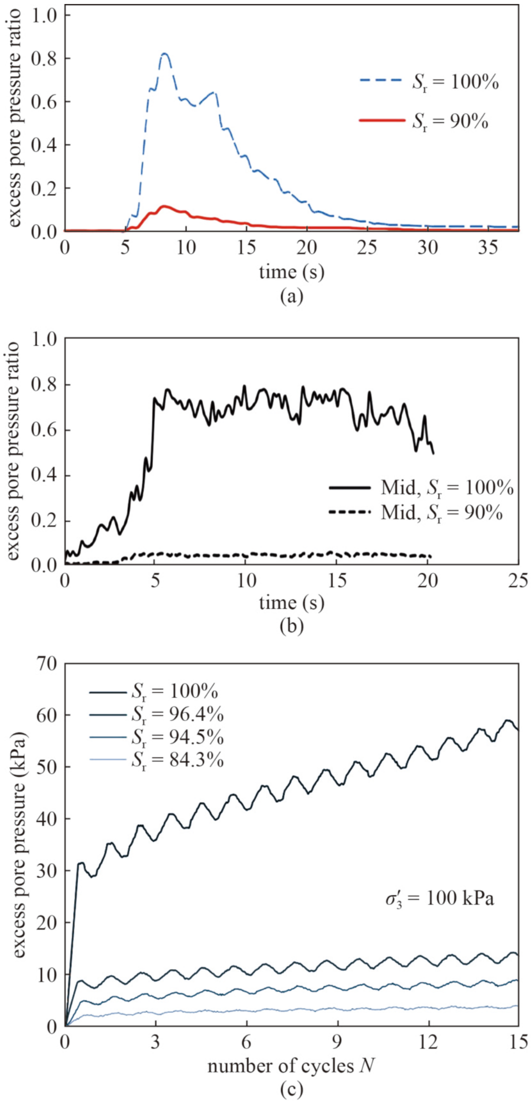

Fig. 4 Development of excess pore pressure for desaturated sand: (a) shaking table test of He et al. [107] (Reprinted from Journal of Zhejiang University. Science A, 17(7), He J, Chu J, Wu S, Peng J, Mitigation of soil liquefaction using microbially induced desaturation, 577–588, Copyright 2016, with permission from Elsevier); (b) shaking table test of Wu [284]; (c) triaxial tests of Wang et al. [287].

6 Examples of up-scaled and field trial of biogeotechnology

In the laboratory, biogeotechnologies have shown excellent efficiency in improving or modifying soil engineering properties. To realize such potential of biogeotechnologies in future engineering practices, conducting up-scaled tests or field trial are necessary. Based on laboratory bench-scale column test or small model test, several up-scaled experiments and field trials have been carried out worldwide. Those trials mainly focused on the feasibility of application of biogeotechnologies in the field, proper deploying measures, monitoring techniques, and the post-improvement evaluating means. All of which contribute to the efficient and reproducible soil improvement process based on biogeotechnology.

6.1 Up-scaled experiments

Several up-scaled model tests have been reported regarding the feasibility of biocementation as a soil improvement technique at a large experimental scale [68,235,290–293]. van Paassen et al. [291,292], first applied the MICP technique to a 1 m^3 sand deposit and turned it into a sand block with substantial UC strength values. Based on the experience gained, two 100 m^3 fine sand pilot tests were performed by Deltares (NL) [235,291] and Soletanche Bachy [290], respectively. A total volume of 100 m^3 of cementation solution was circulated through the 100 m^3 sand deposit during 12 d using injection and extraction wells. The time-lapse shear-wave seismic measurements were also conducted to monitor the biogrouting process during treatment. UC strength tests on cored samples showed peak strength up to 12 MPa. The Young's modulus reached 8500 MPa. However, the amount of precipitated calcium carbonate was spatially dispersed. It could be due to the heterogeneity of bacteria and cementation solution distribution and preferential flow paths, leading to higher calcium carbonate crystal settlement than other non-preferential flow areas. Recently, Wu et al. [293] first carried out a large-scale biogrouting test on sand and rock mixture material, extending the biocementation to a broader scope of application. As shown in Fig. 5, a 1-m^3 container filled with sand and rock was turned into a hard piece of block after two weeks of two-phase biogrouting treatment.

6.2 Field applications

Employing microbiological activity in water flow control was one of the earliest field applications of biogeotechnology. Johnston et al. [294] pumping nutrient and amendment solution for the biostimulation in a site located in South Australia that was contaminated with diesel and gasoline. The 2.25-d biostimulation led to a significant increase in biomass concentration and EPS concentration, translating to a 5-fold decrease in permeability. A similar biobarrier was established to measure the extent of bioclogging and stability in a well-characterized fracture bedrock site located in Southern Ontario, Canada [295]. After 43-d biostimulation of the biofilm growth and 179-d starvation on biofilm persistence, an overall 3.3-logs of hydraulic conductivity reduction were observed for the 222-d experiment [296].

Fig. 5 Up-scaled model tests: 1 m^3 sand model of Wu et al. [293].

Other successful field trials of bioclogging were also reported in the Netherlands and Austria to reduce leakage through water-retaining constructions [297,298]. Besides biofilm, the precipitation of calcium carbonate through the MICP process was also employed in situ for fractured rock sealing and permeability reduction [299,300]. In the study, MICP was promoted in a fractured sandstone layer within the Fayette Sandstone Formation 340.8 m below ground surface. After 24 cementation solutions and 6 microbial suspension injections, the injectivity was decreased more than 3 times and a significant reduction in the in-well pressure falloff was observed [300]. They also presented results of enhancing wellbore cement integrity with MICP in a field-scale demonstration [301].

Another field trial highlighted the use of biocementation to biologically cement and stabilize the gravels around a gas pipeline in the south of the Netherlands [292]. A soil volume of 1000 m^3 was treated using the biogrouting procedure at a depth varying between 3 and 29 m below the surface. There were 200 m^3 of bacterial suspension and 300 to 600 m^3 of cementation solution injected to cement the gravel layer. After treatment, the gravel appeared to be heterogeneously packed, and the shear strength increased with the number of flushes. Besides the traditional injection approach, Gomez et al. [302] performed a field-scale MICP via surface percolation at a mine site location in Saskatchewan, Canada. Results show that a thickness of 2.5 cm stiff crust was formed after 20 d of treatment. Improvement was assessed to a depth of 40 cm using dynamic cone penetration (DCP) testing and calcium carbonate content measurements. A water-jet impingement erosion test was performed, and the result verified the effectiveness of the MICP as a dust control measure.

Stimulation of selective native microorganisms (biostimulation) instead of introducing foreign strains (bioaugmentation) for biocementation in the field would be able to alleviate the concerns of ecological and environmental impact. Gomez et al. [303] conducted a large-scale comparison of biostimulation and bioaugmentation approaches for biocementation in sands. Two identical sand specimens were made with the same dimension of 0.5 m high, 1.7 m diameter, and 0.3 m thickness. MICP treatment was applied in two treatment phases over 12 d. The results suggest that native ureolytic microorganisms may be biostimulated to induce biocementation and significantly improve loose sands at the meter scale. The post-treatment strength was evaluated by cone penetrometer and geophysical measurements. The shear wave velocity of biocemented sand reaches between 131 and 967 m/s, and mid-depth cone penetration resistances range between 3.6 and 32.1 MPa [304]. At highly cemented locations near injection points in both tanks, soil shear wave velocities and cone penetration resistances improved by over 600% and 500%, respectively [305]. In another study, microbes cultivated at depth from field samples have shown their ureolytic ability to induce calcium carbonate precipitation at treatment depths up to 12 m for geotechnical ground improvement [51]. These large-scale experiments and pilot trials all indicate the great potential of biogeotechnologies in various engineering applications. At the same time, challenges are also revealed in the implementation of biogeotechnologies in-field.

7 Challenges and strategies for biogeotechnology

As an emerging and promising technique, biogeotechnology has already attracted vast initiatives from both scientific researchers and industrial professionals. Experiments and trials mentioned before really promise an exciting future for this technique. However, all new solutions to tackle traditional problems always come with challenges.

The first challenge is the uniformity of treatment effect. For field application, the uniformity of the treatment is governed by many factors which are not easy to control as those in the laboratory. The microbial members, cementation material, and environmental factors interact simultaneously and affect the treatment process. Although the materials used in biogeotechnologies, such as biocement, are usually in a liquid form with very low viscosity and their implementation does not cause a significant ground disturbance, the introduction of biocement into fine-grade soils is still not effective without soil mixing [3]. Real-time quality control in the treatment process is another challenge for any project to adopt microbial methods. Geophysical methods could be an effective monitoring technique in the treatment process to detect the presence of biogrout in soil. The selection of proper sensors and their deployment mainly rely on the understanding of the biogeochemical process introduced by microorganisms. When the proper monitoring techniques become mature, we can confidently apply biogeotechnologies in the field and alter the operation in time for optimization of the treatment process.

In most of the studies, the cultivation of microorganisms and source for cementation solution (such as calcium for MICP or nitrate for denitrification) are from high-grade chemical reagents which are too expensive for field applications and not sustainable. Organic waste can be a nutrient source for both bacteria growth and fermenting microorganisms in large-scale applications to diminish the cost. Some studies proposed to cultivate the bacteria in non-sterile conditions [45,209] or using inexpensive technical-grade reagents [306], food-grade yeast medium [307], and sanitized media with inexpensive nutrients and water resources [308] to reduce the cost for the in situ application. Using limestone powder derived from aggregate quarries and disposed of industrial biofuel acid to produce calcium source for biocementation can be a cost-effective and sustainable method [126]. Some laboratory tests have been carried out to establish the procedure for using the by-product of limestone mines and corn cobs as the source of biocement. Through a fermentation process, biocementation solutions were produced and applied directly on top of soil or a crushed stone layer. As a result, once this layer dries, a biocemented slab is formed. Eggshells [124], oyster shells [224], and calcareous sand [225] are also reportedly been used as calcium sources. A direct cost comparison of using biocement and normal cement or chemical for treating soils may not be made at this stage due to the production procedures of the biocement. Because the biocement at the current stage is mostly produced in laboratory conditions and may be produced in a factory setting in the future. When a large quantity of biocement is required for the actual construction work, a factory-scale production line must be established. Until then, the cost of biocement can be evaluated realistically. Continuously finding effective and economic measures to produce microorganisms and cementation sources is a critical step in pushing the biogeotechnologies into engineering practices.

Another major concern of biogeotechnologies stems from their environmental impact. The biosafety of in situ biogeotechnology approaches needs to be addressed. The employed microorganisms must be non-pathogenic and non-hazardous. Before any foreign strains or cultures are introduced into the local environment, their genetic information must be identified to ensure their biosafety. Information on the microorganisms, their fate in the environment, and their ecological effects must be available to designers and workers. As an alternative, using the urease for the urea hydrolysis to precipitate the calcium carbonate, so-called Enzyme Induced Calcite Precipitation (EICP) [309–312], could reduce or even avoid the issue of bio-safety. The urease can be extracted from UPB [163,168] or some plant seeds, such as soybean [313], jack bean [314,315], and watermelon seeds [309,316]. Moreover, the production of any potential hazardous and harmful byproduct during the treatment process must be properly collected and treated. Alternatively, different processes should be adopted to avoid the harmful byproduct. For example, to avoid the production of ammonia, denitrification-based biocementation can be employed [15,289,317], although the process is not as effective as MICP at the moment. Overall, the environmental assessment would ensure the sustainability of the biogeotechnology concept.

8 Concluding remarks

Although much attention and resources have been devoted to the use of biotechnologies in geotechnical engineering in the past decades; we are yet to fully understand the mechanisms of different microbial processes and the methods to control the engineering properties of treated soil reliably. In this paper, three major microbial processes, biocementation, bioclogging, biogas desaturation, and their potential applications and influence factors, are reviewed. Examples of up-scaled model tests and pilot trials are introduced. Difficulties and challenges in field implementation, monitoring, cost efficiency, and environmental impacts are also discussed. The microbial processes involved in biogeotechnology usually comes with complicated physical and chemical processes, leading to many uncertainties and difficulties in the research and application of biogeotechnology. To better understand the fundamentals of biogeotechnology and its applications to engineering practices, it is essential to encourage cross-disciplinary collaboration between researchers and industry practitioners. There are still many challenges to overcome before biogeotechnology can be fully adopted in field applications. By integrating experts from different disciplines, a breakthrough would emerge to push the frontier of biogeotechnology and its applications in the future.

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References

1. Mitchell J K, Santamarina J C. Biological considerations in geotechnical engineering. Journal of Geotechnical and Geoenvironmental Engineering, 2005, 131(10): 1222−1233
2. National Research Council. Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation. Washington, D.C.: National Academies Press, 2006
3. DeJong J T, Soga K, Kavazanjian E, Burns S, Van Paassen L A, Al Qabany A, Aydilek A, Bang S S, Burbank M, Caslake L F, Chen C Y, Cheng X, Chu J, Ciurli S, Esnault-Filet A, Fauriel S, Hamdan N, Hata T, Inagaki Y, Jefferis S, Kuo M, Laloui L, Larrahondo J, Manning D A C, Martinez B, Montoya B M, Nelson D C, Palomino A, Renforth P, Santamarina J C, Seagren E A, Tanyu B, Tsesarsky M, Weaver T. Biogeochemical processes and geotechnical applications: Progress, opportunities and challenges. Geotechnique, 2013, 63(4): 287−301
4. Ivanov V, Chu J. Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil *in situ*. Reviews in Environmental Science and Biotechnology, 2008, 7(2): 139−153
5. Dhami N K, Reddy M S, Mukherjee A. Biomineralization of calcium carbonates and their engineered applications: A review. Frontiers in Microbiology, 2013, 4: 314
6. Jiang N J, Tang C S, Hata T, Courcelles B, Dawoud O, Singh D N. Bio-mediated soil improvement: the way forward. Soil Use and Management, 2020, 36(2): 185−188
7. Martinez B C, DeJong J T. Bio-mediated soil improvement: load transfer mechanisms at the micro-and macro-scales. In: Proceedings of the US-China Workshop on Ground Improvement Technology. 2009, 242–251
8. Phillips A J, Gerlach R, Lauchnor E, Mitchell A C, Cunningham A B, Spangler L. Engineered applications of ureolytic biomineralization: A review. Biofouling, 2013, 29(6): 715−733
9. Terzis D, Laloui L. A decade of progress and turning points in the understanding of bio-improved soils: A review. Geomechanics for Energy and the Environment, 2019, 19: 100116
10. Baveye P, Vandevivere P, Hoyle B L, DeLeo P C, de Lozada D S. Environmental impact and mechanisms of the biological clogging of saturated soils and aquifer materials. Critical Reviews in Environmental Science and Technology, 1998, 28(2): 123−191
11. DeJong J, Proto C, Kuo M, Gomez M. Bacteria, biofilms, and invertebrates: The next generation of geotechnical engineers? In: Proceedings of the 2014 Geo-Congress. Atlanta: American Society of Civil Engineers, 2014, 3959–3968
12. He J, Chu J, Ivanov V. Mitigation of liquefaction of saturated sand using biogas. Geotechnique, 2013, 63(4): 267−275
13. O'Donnell S T, Rittmann B E, Kavazanjian E Jr. MIDP: Liquefaction mitigation via microbial denitrification as a two-stage process. I: Desaturation. Journal of Geotechnical and Geoenvironmental Engineering, 2017, 143(12): 04017094
14. DeJong J T, Fritzges M B, Nüsslein K. Microbially induced cementation to control sand response to undrained shear. Journal of Geotechnical and Geoenvironmental Engineering, 2006, 132(11): 1381−1392
15. van Paassen L A, Daza C M, Staal M, Sorokin D Y, van der Zon W, van Loosdrecht M C M. Potential soil reinforcement by biological denitrification. Ecological Engineering, 2010, 36(2): 168−175
16. Warthmann R, Van Lith Y, Vasconcelos C, McKenzie J A, Karpoff A M. Bacterially induced dolomite precipitation in

anoxic culture experiments. Geology, 2000, 28(12): 1091−1094

17. Ivanov V, Chu J, Stabnikov V. Iron- and calcium-based biogrouts for porous soils. Proceedings of the Institution of Civil Engineers-Construction Materials, 2014, 167(1): 36−41
18. Roden E E, Urrutia M M. Influence of biogenic Fe (II) on bacterial crystalline Fe (III) oxide reduction. Geomicrobiology Journal, 2002, 19(2): 209−251
19. Yu X, Jiang J. Mineralization and cementing properties of bio-carbonate cement, bio-phosphate cement, and bio-carbonate/phosphate cement: a review. Environmental Science and Pollution Research International, 2018, 25(22): 21483−21497
20. Beato C, Fernández M S, Fermani S, Reggi M, Neira-Carrillo A, Rao A, Falini G, Arias J L. Calcium carbonate crystallization in tailored constrained environments. CrystEngComm, 2015, 17(31): 5953−5961
21. Wang Y Z, Soga K, DeJong J T, Kabla A J. A microfluidic chip and its use in characterising the particle-scale behaviour of microbial-induced calcium carbonate precipitation (MICP). Geotechnique, 2019, 69(12): 1086−1094
22. Wang Y, Soga K, DeJong J T, Kabla A J. Microscale visualization of microbial-induced calcium carbonate precipitation processes. Journal of Geotechnical and Geoenvironmental Engineering, 2019, 145(9): 04019045
23. Dupraz S, Parmentier M, Ménez B, Guyot F. Experimental and numerical modeling of bacterially induced pH increase and calcite precipitation in saline aquifers. Chemical Geology, 2009, 265(1−2): 44−53
24. Ghosh T, Bhaduri S, Montemagno C, Kumar A. Sporosarcina pasteurii can form nanoscale calcium carbonate crystals on cell surface. PLoS One, 2019, 14(1): e0210339
25. Hammes F, Boon N, de Villiers J, Verstraete W, Siciliano S D. Strain-specific ureolytic microbial calcium carbonate precipitation. Applied and Environmental Microbiology, 2003, 69(8): 4901−4909
26. Stocks-Fischer S, Galinat J K, Bang S S. Microbiological precipitation of $CaCO_3$. Soil Biology & Biochemistry, 1999, 31(11): 1563−1571
27. Jimenez-Lopez C, Jroundi F, Rodríguez-Gallego M, Arias J M, Gonzalez-Muñoz M T. Biomineralization induced by Myxobacteria. Communicating Current Eesearch and Educational Ropics and Trends in Applied Microbiology, 2007, 1: 143−154
28. Gleaton J, Lai Z, Xiao R, Chen Q, Zheng Y. Microalga-induced biocementation of martian regolith simulant: Effects of biogrouting methods and calcium sources. Construction & Building Materials, 2019, 229: 116885
29. Bachmeier K L, Williams A E, Warmington J R, Bang S S. Urease activity in microbiologically-induced calcite precipitation. Journal of Biotechnology, 2002, 93(2): 171−181
30. Sharma M, Satyam N, Reddy K R. Rock-like behavior of biocemented sand treated under non-sterile environment and various treatment conditions. Journal of Rock Mechanics and Geotechnical Engineering, 2021, 13(3): 705−716
31. Whitaker J M, Vanapalli S, Fortin D. Improving the strength of sandy soils via ureolytic $CaCO_3$ solidification by Sporosarcina ureae. Biogeosciences, 2018, 15(14): 4367−4380
32. Al-Thawadi S, Cord-Ruwisch R. Calcium carbonate crystals formation by ureolytic bacteria isolated from Australian soil and sludge. Journal of Advanced Science and Engineering Research, 2012, 2(1): 12−26
33. Amarakoon G G N N, Kawasaki S. Factors affecting sand solidification using MICP with Pararhodobacter sp. Materials Transactions, 2018, 59(1): 72−81
34. Arunachalam K D, Sathyanarayanan K S, Darshan B S, Raja R B. Studies on the characterisation of Biosealant properties of Bacillus sphaericus. International Journal of Engineering Science and Technology, 2010, 2(3): 270−277
35. Badiee H, Sabermahani M, Tabandeh F, Saeedi Javadi A. Application of an indigenous bacterium in comparison with Sporosarcina pasteurii for improvement of fine granular soil. International Journal of Environmental Science and Technology, 2019, 16(12): 8389−8400
36. Charpe A U, Latkar M V. Effect of biocementation using soil bacteria to augment the mechanical properties of cementitious materials. Materials Today: Proceedings, 2020, 21: 1218−1222
37. Chu J, Stabnikov V, Ivanov V. Microbially induced calcium carbonate precipitation on surface or in the bulk of soil. Geomicrobiology Journal, 2012, 29(6): 544−549
38. Danjo T, Kawasaki S. Microbially induced sand cementation method using Pararhodobacter sp. strain SO1, inspired by beachrock formation mechanism. Materials Transactions, 2016, 57(3): 428−437
39. Ghosh P, Mandal S, Pal S, Bandyopadhyaya G, Chattopadhyay B D. Development of bioconcrete material using an enrichment culture of novel thermophilic anaerobic bacteria. Indian Journal of Experimental Biology, 2006, 44: 336−339
40. Nemati M, Greene E A, Voordouw G. Permeability profile modification using bacterially formed calcium carbonate: Comparison with enzymic option. Process Biochemistry, 2005, 40(2): 925−933
41. Tsesarsky M, Gat D, Ronen Z. Biological aspects of microbial-induced calcite precipitation. Environmental Geotechnics, 2018, 5(2): 69−78
42. Umar M, Kassim K A, Zango M U, Muhammed A S. Performance evaluation of lime and microbial cementation in residual soil improvement. IOP Conference Series: Materials Science and Engineering, 2019, 527(1): 012005
43. Yang Z, Cheng X. A performance study of high-strength microbial mortar produced by low pressure grouting for the reinforcement of deteriorated masonry structures. Construction & Building Materials, 2013, 41: 505−515
44. Fujita Y, Ferris F G, Lawson R D, Colwell F S, Smith R W. Calcium carbonate precipitation by ureolytic subsurface bacteria. Geomicrobiology Journal, 2000, 17(4): 305−318
45. Cheng L, Cord-Ruwisch R. Selective enrichment and production of highly urease active bacteria by non-sterile (open) chemostat culture. Journal of Industrial Microbiology & Biotechnology, 2013, 40(10): 1095−1104
46. Yang Y, Chu J, Cao B, Liu H, Cheng L. Biocementation of soil using non-sterile enriched urease-producing bacteria from activated sludge. Journal of Cleaner Production, 2020, 262: 121315
47. Amini Kiasari M, Pakbaz M S, Ghezelbash G R. Increasing of soil urease activity by stimulation of indigenous bacteria and investigation of their role on shear strength. Geomicrobiology

Journal, 2018, 35(10): 821−828

48. Burbank M, Weaver T, Lewis R, Williams T, Williams B, Crawford R. Geotechnical tests of sands following bioinduced calcite precipitation catalyzed by indigenous bacteria. Journal of Geotechnical and Geoenvironmental Engineering, 2013, 139(6): 928−936
49. Gat D, Ronen Z, Tsesarsky M. Soil bacteria population dynamics following stimulation for ureolytic microbial-induced $CaCO_3$ precipitation. Environmental Science & Technology, 2016, 50(2): 616−624
50. Gat D, Ronen Z, Tsesarsky M. Long-term sustainability of microbial-induced $CaCO_3$ precipitation in aqueous media. Chemosphere, 2017, 184: 524−531
51. Gomez M G, Graddy C M R, DeJong J T, Nelson D C, Tsesarsky M. Stimulation of native microorganisms for biocementation in samples recovered from field-scale treatment depths. Journal of Geotechnical and Geoenvironmental Engineering, 2018, 144(1): 04017098
52. Islam M T, Chittoori B C S, Burbank M. Evaluating the applicability of biostimulated calcium carbonate precipitation to stabilize clayey soils. Journal of Materials in Civil Engineering, 2020, 32(3): 04019369
53. Kannan K, Bindu J, Vinod P. Engineering behaviour of MICP treated marine clays. Marine Georesources and Geotechnology, 2020, 38(7): 761−769
54. Liu P, Shao G, Huang R. Study of the interactions between S. pasteurii and indigenous bacteria and the effect of these interactions on the MICP. Arabian Journal of Geosciences, 2019, 12(23): 724
55. Ramachandran A L, Polat P, Mukherjee A, Dhami N K. Understanding and creating biocementing beachrocks via biostimulation of indigenous microbial communities. Applied Microbiology and Biotechnology, 2020, 104(8): 3655−3673
56. Wang Y J, Han X L, Jiang N J, Wang J, Feng J. The effect of enrichment media on the stimulation of native ureolytic bacteria in calcareous sand. International Journal of Environmental Science and Technology, 2020, 17(3): 1795−1808
57. Chu J, Ivanov V, He J, Naeimi M, Li B, Stabnikov V. Development of microbial geotechnology in Singapore. In: Proceedings of Geo-Frontiers 2011 Advances in Geotechnical Engineering. Dallas: ASCE, 2011, 4070–4078
58. Chu J, Ivanov V, He J, Maeimi M, Wu S. Use of Biogeotechnologies for Soil Improvement. Ground Improvement Case Histories. Oxford: Butterworth-Heinemann, 2015, 571–589
59. DeJong J T, Mortensen B M, Martinez B C, Nelson D C. Bio-mediated soil improvement. Ecological Engineering, 2010, 36(2): 197−210
60. DeJong J T, Soga K, Banwart S A, Whalley W R, Ginn T R, Nelson D C, Mortensen B M, Martinez B C, Barkouki T. Soil engineering in vivo: Harnessing natural biogeochemical systems for sustainable, multi-functional engineering solutions. Journal of the Royal Society, Interface, 2011, 8(54): 1−15
61. Haouzi F Z, Courcelles B. Major applications of MICP sand treatment at multi-scale levels: A review. In: Proceedings of 71st Canadian Geotechnical Conference and 13th Joint CGS/IAH-CNC Groundwater Conference. Richmond: Canadian Geotechnical Society, 2018
62. Chae S H, Chung H, Nam K. Evaluation of microbially Induced calcite precipitation (MICP) methods on different soil types for wind erosion control. Environmental Engineering Research, 2021, 26(1): 190507
63. Jiang N J, Soga K, Kuo M. Microbially induced carbonate precipitation for seepage-induced internal erosion control in sand–clay mixtures. Journal of Geotechnical and Geoenvironmental Engineering, 2017, 143(3): 04016100
64. Jiang N J, Tang C S, Yin L Y, Xie Y H, Shi B. Applicability of microbial calcification method for sandy-slope surface erosion control. Journal of Materials in Civil Engineering, 2019, 31(11): 04019250
65. Jiang N J, Soga K. Erosional behavior of gravel-sand mixtures stabilized by microbially induced calcite precipitation (MICP). Soil and Foundation, 2019, 59(3): 699−709
66. Liu S, Wang R, Yu J, Peng X, Cai Y, Tu B. Effectiveness of the anti-erosion of an MICP coating on the surfaces of ancient clay roof tiles. Construction & Building Materials, 2020, 243: 118202
67. Maleki M, Ebrahimi S, Asadzadeh F, Emami Tabrizi M. Performance of microbial-induced carbonate precipitation on wind erosion control of sandy soil. International Journal of Environmental Science and Technology, 2016, 13(3): 937−944
68. Salifu E, MacLachlan E, Iyer K R, Knapp C W, Tarantino A. Application of microbially induced calcite precipitation in erosion mitigation and stabilisation of sandy soil foreshore slopes: A preliminary investigation. Engineering Geology, 2016, 201: 96−105
69. Van der Ruyt M, van der Zon W. Biological in situ reinforcement of sand in near-shore areas. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 2009, 162(1): 81−83
70. Gerbersdorf S U, Jancke T, Westrich B, Paterson D M. Microbial stabilization of riverine sediments by extracellular polymeric substances. Geobiology, 2008, 6(1): 57−69
71. Bang S C, Min S H, Bang S S. KGS Awards Lectures: Application of microbiologically induced soil stabilization technique for dust suppression. International Journal of Geo-Engineering, 2011, 3(2): 27−37
72. Meyer F D, Bang S, Min S, Stetler L D, Bang S S. Microbiologically-induced soil stabilization: Application of Sporosarcina pasteurii for fugitive dust control. In: Proceedings of Geo-Frontiers 2011. Dallas: American Society of Civil Engineers, 2011, 4002–4011
73. Naeimi M, Chu J. Comparison of conventional and bio-treated methods as dust suppressants. Environmental Science and Pollution Research International, 2017, 24(29): 23341−23350
74. Stabnikov V, Naeimi M, Ivanov V, Chu J. Formation of water-impermeable crust on sand surface using biocement. Cement and Concrete Research, 2011, 41(11): 1143−1149
75. Stabnikov V, Chu J, Myo A N, Ivanov V. Immobilization of sand dust and associated pollutants using bioaggregation. Water, Air, and Soil Pollution, 2013, 224(9): 1631
76. Abo-El-Enein S A, Ali A H, Talkhan F N, Abdel-Gawwad H A. Utilization of microbial induced calcite precipitation for sand consolidation and mortar crack remediation. HBRC Journal, 2012, 8(3): 185−192
77. Achal V, Mukerjee A, Sudhakara Reddy M. Biogenic treatment improves the durability and remediates the cracks of concrete

structures. Construction & Building Materials, 2013, 48: 1−5

78. Van Tittelboom K, De Belie N, De Muynck W, Verstraete W. Use of bacteria to repair cracks in concrete. Cement and Concrete Research, 2010, 40(1): 157−166
79. Yang Z, Cheng X, Li M. Engineering properties of MICP-bonded sandstones used for historical masonry building restoration. In: Proceedings of Geo-Frontiers 2011. Dallas: American Society of Civil Engineers, 2011, 4031–4040
80. De Muynck W, De Belie N, Verstraete W. Microbial carbonate precipitation in construction materials: A review. Ecological Engineering, 2010, 36(2): 118−136
81. De Muynck W, Verbeken K, De Belie N, Verstraete W. Influence of urea and calcium dosage on the effectiveness of bacterially induced carbonate precipitation on limestone. Ecological Engineering, 2010, 36(2): 99−111
82. De Muynck W, Leuridan S, Van Loo D, Verbeken K, Cnudde V, De Belie N, Verstraete W. Influence of pore structure on the effectiveness of a biogenic carbonate surface treatment for limestone conservation. Applied and Environmental Microbiology, 2011, 77(19): 6808−6820
83. De Muynck W, Verbeken K, De Belie N, Verstraete W. Influence of temperature on the effectiveness of a biogenic carbonate surface treatment for limestone conservation. Applied Microbiology and Biotechnology, 2013, 97(3): 1335−1347
84. Rodriguez-Navarro C, Rodriguez-Gallego M, Ben Chekroun K, Gonzalez-Munoz M T. Conservation of ornamental stone by Myxococcus xanthus-induced carbonate biomineralization. Applied and Environmental Microbiology, 2003, 69(4): 2182−2193
85. Cheng L, Shahin M A, Mujah D. Influence of key environmental conditions on microbially induced cementation for soil stabilization. Journal of Geotechnical and Geoenvironmental Engineering, 2017, 143(1): 04016083
86. Sharma M, Satyam N, Reddy K R. Effect of freeze−thaw cycles on engineering properties of biocemented sand under different treatment conditions. Engineering Geology, 2021, 284: 106022
87. Abbasi B, Ta H X, Muhunthan B, Ramezanian S, Abu-Lail N, Kwon T H. Modeling of Permeability Reduction in Bioclogged Porous Sediments. Journal of Geotechnical and Geoenvironmental Engineering, 2018, 144(4): 04018016
88. Flemming H C, Wingender J. The biofilm matrix. Nature Reviews. Microbiology, 2010, 8(9): 623−633
89. Ng C W W, So P S, Coo J L, Zhou C, Lau S Y. Effects of biofilm on gas permeability of unsaturated sand. Geotechnique, 2019, 69(10): 917−923
90. Farah T, Souli H, Fleureau J M, Kermouche G, Fry J J, Girard B, Aelbrecht D, Lambert J, Harkes M. Durability of Bioclogging Treatment of Soils. Journal of Geotechnical and Geoenvironmental Engineering, 2016, 142(9): 04016040
91. Muthukkumaran K, Shashank B S. Durability of microbially induced calcite precipitation (micp) treated cohesionless soils. Japanese Geotechnical Society Special Publication, 2016, 2(56): 1946−1949
92. Jiang N J, Soga K. The applicability of microbially induced calcite precipitation (MICP) for internal erosion control in gravel-sand mixtures. Geotechnique, 2017, 67(1): 42−55
93. Clarà Saracho A, Haigh S K, Ehsan Jorat M. Flume study on the effects of microbial induced calcium carbonate precipitation (MICP) on the erosional behaviour of fine sand. Geotechnique, 2020: 1–15
94. Chu J, Ivanov V, Stabnikov V, Li B. Microbial method for construction of an aquaculture pond in sand. Geotechnique, 2013, 63(10): 871−875
95. Stabnikov V, Ivanov V, Chu J. Sealing of sand using spraying and percolating biogrouts for the construction of model aquaculture pond in arid desert. International Aquatic Research, 2016, 8(3): 207−216
96. Minto J M, MacLachlan E, El Mountassir G, Lunn R J. Rock fracture grouting with microbially induced carbonate precipitation. Water Resources Research, 2016, 52(11): 8827−8844
97. Wu C Z, Chu J, Wu S F, Hong Y. 3D characterization of microbially induced carbonate precipitation in rock fracture and the resulted permeability reduction. Engineering Geology, 2019, 249: 23−30
98. Wu C Z, Chu J, Wu S F, Cheng L, van Paassen L A. Microbially induced calcite precipitation along a circular flow channel under a constant flow condition. Acta Geotechnica, 2019, 14(3): 673−683
99. Wu C Z, Chu J, Wu S F, Guo W. Quantifying the permeability reduction of biogrouted rock fracture. Rock Mechanics and Rock Engineering, 2019, 52(3): 947−954
100. Wu S F, Chu J, Wu C Z. Biogrouting for Seepage Control for Rock Joints. In: ISRM International Symposium—10th Asian Rock Mechanics Symposium. Singapore: International Society for Rock Mechanics and Rock Engineering, 2018
101. Qian C X, Wang J Y, Wang R X, Cheng L. Corrosion protection of cement-based building materials by surface deposition of $CaCO_3$ by *Bacillus pasteurii*. Materials Science and Engineering C, 2009, 29(4): 1273−1280
102. Gollapudi U K, Knutson C L, Bang S S, Islam M R. A new method for controlling leaching through permeable channels. Chemosphere, 1995, 30(4): 695−705
103. MacLeod F A, Lappin-Scott H M, Costerton J W. Plugging of a model rock system by using starved bacteria. Applied and Environmental Microbiology, 1988, 54(6): 1365−1372
104. Zhong L, Islam M. A new microbial plugging process and its impact on fracture remediation. In: SPE Annual Technical Conference and Exhibition. Dallas: Society of Petroleum Engineers, 1995
105. O'Donnell S T, Hall C A, Kavazanjian E Jr, Rittmann B E. Biogeochemical model for soil improvement by denitrification. Journal of Geotechnical and Geoenvironmental Engineering, 2019, 145(11): 04019091
106. O'Donnell S T, Rittmann B E, Kavazanjian E Jr. Factors controlling microbially induced desaturation and precipitation (MIDP) via denitrification during continuous flow. Geomicrobiology Journal, 2019, 36(6): 543−558
107. He J, Chu J, Wu S, Peng J. Mitigation of soil liquefaction using microbially induced desaturation. Journal of Zhejiang University. Science A, 2016, 17(7): 577−588
108. He J, Chu J, Gao Y, Liu H. Research advances and challenges in biogeotechnologies. Geotechnical Research, 2019, 6(2): 144−155
109. Carlson C A, Ingraham J L. Comparison of denitrification by *Pseudomonas stutzeri*, *Pseudomonas aeruginosa*, and *Paracoccus*

denitrificans. Applied and Environmental Microbiology, 1983, 45(4): 1247−1253

110. Peng E X, Zhang D W. Prevention of liquefaction of saturated sand using biogas produced by *Pseudomonas stutzeri*. In: 2017 International Conference on Transportation Infrastructure and Materials (ICTIM 2017). Qingdao: DEStech Transactions on Materials Science and Engineering, 2017
111. O'Donnell S T, Kavazanjian E Jr, Rittmann B E. MIDP: Liquefaction mitigation via microbial denitrification as a two-stage process. II: MICP. Journal of Geotechnical and Geoenvironmental Engineering, 2017, 143(12): 04017095
112. Saggar S, Jha N, Deslippe J, Bolan N, Luo J, Giltrap D, Kim D G, Zaman M, Tillman R. Denitrification and N_2O: N_2 production in temperate grasslands: Processes, measurements, modelling and mitigating negative impacts. Science of the Total Environment, 2013, 465: 173−195
113. Chou C, Seagren E, Aydilek A, Lai M. Biocalcification of sand through ureolysis. Journal of Geotechnical and Geoenvironmental Engineering, 2011, 137(12): 1179−1189
114. Do J, Montoya B M, Gabr M A. Debonding of microbially induced carbonate precipitation-stabilized sand by shearing and erosion. Geomechanics and Engineering. International Journal (Toronto, Ont.), 2019, 17(5): 429−438
115. Feng K, Montoya B. Influence of confinement and cementation level on the behavior of microbial-induced calcite precipitated sands under monotonic drained loading. Journal of Geotechnical and Geoenvironmental Engineering, 2016, 142(1): 04015057
116. Feng Z, Zhao Y, Zeng W, Lu Z, Shah S P. Using microbial carbonate precipitation to improve the properties of recycled fine aggregate and mortar. Construction & Building Materials, 2020, 230: 116949
117. Gai X, Sánchez M. An elastoplastic mechanical constitutive model for microbially mediated cemented soils. Acta Geotechnica, 2019, 14(3): 709−726
118. Liu L, Liu H, Stuedlein A W, Evans T M, Xiao Y. Strength, stiffness, and microstructure characteristics of biocemented calcareous sand. Canadian Geotechnical Journal, 2019, 56(10): 1502−1513
119. Nafisi A, Mocelin D, Montoya B M, Underwood S. Tensile strength of sands treated with microbially induced carbonate precipitation. Canadian Geotechnical Journal, 2020, 57(10): 1611−1616
120. Shanahan C, Montoya B M. Strengthening coastal sand dunes using microbial-induced calcite precipitation. In: Proceedings of the 2014 Geo-Congress. Atlanta: American Society of Civil Engineers, 2014: 1683–1692
121. Sharma A, Ramkrishnan R. Study on effect of microbial induced calcite precipitates on strength of fine grained soils. Perspectives in Science, 2016, 8: 198−202
122. Thomas O'Donnell S, Kavazanjian E Jr. Stiffness and dilatancy improvements in uncemented sands treated through MICP. Journal of Geotechnical and Geoenvironmental Engineering, 2015, 141(11): 02815004
123. Bernardi D, DeJong J T, Montoya B M, Martinez B C. Bio-bricks: Biologically cemented sandstone bricks. Construction & Building Materials, 2014, 55: 462−469
124. Choi S G, Wu S, Chu J. Biocementation for sand using an eggshell as calcium source. Journal of Geotechnical and Geoenvironmental Engineering, 2016, 142(10): 06016010
125. Choi S G, Wang K, Chu J. Properties of biocemented, fiber reinforced sand. Construction & Building Materials, 2016, 120: 623−629
126. Choi S G, Chu J, Brown R C, Wang K, Wen Z. Sustainable biocement production via microbially induced calcium carbonate precipitation: Use of limestone and acetic acid derived from pyrolysis of lignocellulosic biomass. ACS Sustainable Chemistry & Engineering, 2017, 5(6): 5183−5190
127. Chu J, Ivanov V, Naeimi M, Stabnikov V, Liu H L. Optimization of calcium-based bioclogging and biocementation of sand. Acta Geotechnica, 2014, 9(2): 277−285
128. He J, Chu J. Cementation of sand due to salt precipitation in drying process. Marine Georesources and Geotechnology, 2017, 35(3): 441−445
129. Lee M L, Ng W S, Tanaka Y. Stress-deformation and compressibility responses of bio-mediated residual soils. Ecological Engineering, 2013, 60: 142−149
130. Waldschmidt J B, Courcelles B. Influence of resting periods on the efficiency of microbially induced calcite precipitation (MICP) in non-saturated conditions. In: International Congress and Exhibition "Sustainable Civil Infrastructures". Springer, Cham, 2019, 119–126
131. Xiao Y, Yuan Z, Lin J, Ran J, Dai B, Chu J, Liu H. Effect of particle shape of glass beads on the strength and deformation of cemented sands. Acta Geotechnica, 2019, 14(6): 2123−2131
132. Xiao Y, Wang Y, Desai C S, Jiang X, Liu H. Strength and deformation responses of biocemented sands using a temperature-controlled method. International Journal of Geomechanics, 2019, 19(11): 04019120
133. Venuleo S, Laloui L, Terzis D, Hueckel T, Hassan M. Microbially induced calcite precipitation effect on soil thermal conductivity. Géotechnique Letters, 2016, 6(1): 39−44
134. Wang Z, Zhang N, Ding J, Li Q, Xu J. Thermal conductivity of sands treated with microbially induced calcite precipitation (MICP) and model prediction. International Journal of Heat and Mass Transfer, 2020, 147: 118899
135. Choi S G, Hoang T, Alleman E J, Chu J. Splitting tensile strength of fiber-reinforced and biocemented sand. Journal of Materials in Civil Engineering, 2019, 31(9): 06019007
136. Choi S G, Hoang T, Park S S. Undrained behavior of microbially induced calcite precipitated sand with polyvinyl alcohol fiber. Applied Sciences (Basel, Switzerland), 2019, 9(6): 1214
137. Lei X W, Lin S Q, Meng Q S, Liao X, Xu J. Influence of different fiber types on properties of biocemented calcareous sand. Arabian Journal of Geosciences, 2020, 13(8): 317
138. Li M, Li L, Ogbonnaya U, Wen K, Tian A, Amini F. Influence of fiber addition on mechanical properties of MICP-treated sand. Journal of Materials in Civil Engineering, 2016, 28(4): 04015166
139. Li L, Li M, Ogbonnaya U, Wen K, Xu Y, Amini F. Study of a discrete randomly distributed fiber on the tensile strength improvement of microbial-induced soil stabilization. In: Geotechnical Frontiers 2017. Orlando: American Society of Civil Engineers, 2017, 12–18
140. Liu S, Wen K, Armwood C, Bu C, Li C, Amini F, Li L. Enhancement of MICP-treated sandy soils against environmental

deterioration. Journal of Materials in Civil Engineering, 2019, 31(12): 04019294

141. Xiao Y, He X, Evans T M, Stuedlein A W, Liu H. Unconfined compressive and splitting tensile strength of basalt fiber–reinforced biocemented sand. Journal of Geotechnical and Geoenvironmental Engineering, 2019, 145(9): 04019048
142. Yao D F, Wu J, Wang G W, Wang P B, Zheng J J, Yan J Y, Xu L, Yan Y J. Effect of wool fiber addition on the reinforcement of loose sands by microbially induced carbonate precipitation (MICP): Mechanical property and underlying mechanism. Acta Geotechnica, 2021, 16(5): 1401−1416
143. Zhao Y, Fan C, Ge F, Cheng X, Liu P. Enhancing strength of MICP-treated sand with scrap of activated carbon-fiber felt. Journal of Materials in Civil Engineering, 2020, 32(4): 04020061
144. Hamdan N, Zhao Z, Mujica M, Kavazanjian E Jr, He X. Hydrogel-assisted enzyme-induced carbonate mineral precipitation. Journal of Materials in Civil Engineering, 2016, 28(10): 04016089
145. Wang X R, Tao J L, Bao R T, Tran T, Tucker-Kulesza S. Surficial soil stabilization against water-induced erosion using polymer-modified microbially induced carbonate precipitation. Journal of Materials in Civil Engineering, 2018, 30(10): 04018267
146. Wang X R, Tao J L. Polymer-modified microbially induced carbonate precipitation for one-shot targeted and localized soil improvement. Acta Geotechnica, 2019, 14(3): 657−671
147. Cheng L, Yang Y, Chu J. *In-situ* microbially induced Ca^{2+}-alginate polymeric sealant for seepage control in porous materials. Microbial Biotechnology, 2019, 12(2): 324−333
148. Ivanov V, Chu J, Stabnikov V, Li B. Strengthening of soft marine clay using bioencapsulation. Marine Georesources and Geotechnology, 2015, 33(4): 320−324
149. Liu B, Zhu C, Tang C S, Xie Y H, Yin L Y, Cheng Q, Shi B. Bio-remediation of desiccation cracking in clayey soils through microbially induced calcite precipitation (MICP). Engineering Geology, 2020, 264: 105389
150. Rebata-Landa V. Microbial activity in sediments: Effects on soil behavior. Dissertation for the Doctoral Degree. Atlanta: Georgia Institute of Technology, 2007
151. Kim D, Park K, Kim D. Effects of ground conditions on microbial cementation in soils. Materials (Basel), 2013, 7(1): 143−156
152. Lee M L, Ng W S, Tan C K, Hii S L. Bio-mediated soil improvement under various concentrations of cementation reagent. Applied Mechanics and Materials, 2012, 204: 326−329
153. Ng W S, Lee M L, Hii S L. An overview of the factors affecting microbial-induced calcite precipitation and its potential application in soil improvement. World Academy of Science, Engineering and Technology, 2012, 62(2): 723−729
154. Soon N W, Lee L M, Khun T C, Ling H S. Improvements in engineering properties of soils through microbial-induced calcite precipitation. KSCE Journal of Civil Engineering, 2013, 17(4): 718−728
155. Soon N W, Lee L M, Khun T C, Ling H S. Factors affecting improvement in engineering properties of residual soil through microbial-induced calcite precipitation. Journal of Geotechnical and Geoenvironmental Engineering, 2014, 140(5): 04014006
156. Safavizadeh S, Montoya B M, Gabr M A. Effect of Microbial Induced Calcium Carbonate Precipitation on the Performance of Ponded Coal Ash. Kentucky: Association of State Dam Safety Officials, Inc., 2017
157. Zhang J, Wen K, Li L. Leaching assessment of MICP-treated coal combustion products in roadways embankment. In: Eighth International Conference on Case Histories in Geotechnical Engineering (Geo-Congress 2019). Philadelphia: American Society of Civil Engineers, 2019
158. Chittoori B C S, Rahman T, Burbank M, Moghal A A B. Evaluating shallow mixing protocols as application methods for microbial induced calcite precipitation targeting expansive soil treatment. In: Eighth International Conference on Case Histories in Geotechnical Engineering. Philadelphia: American Society of Civil Engineers, 2019
159. Liu S, Yu J, Peng X, Cai Y, Tu B. Preliminary study on repairing tabia cracks by using microbially induced carbonate precipitation. Construction & Building Materials, 2020, 248: 118611
160. Cardoso R, Pires I, Duarte S O D, Monteiro G A. Effects of clay's chemical interactions on biocementation. Applied Clay Science, 2018, 156: 96−103
161. Sasaki T, Kuwano R. Undrained cyclic triaxial testing on sand with non-plastic fines content cemented with microbially induced $CaCO_3$. Soil and Foundation, 2016, 56(3): 485−495
162. Sun X, Miao L, Chen R. Effects of different clay's percentages on improvement of sand-clay mixtures with microbially induced calcite precipitation. Geomicrobiology Journal, 2019, 36(9): 810−818
163. Hoang T, Alleman J, Cetin B, Ikuma K, Choi S G. Sand and silty-sand soil stabilization using bacterial enzyme-induced calcite precipitation (BEICP). Canadian Geotechnical Journal, 2019, 56(6): 808−822
164. Ibrahim M A, Al-Omari R R, Ibrahim M H. Experimental study to improve the shear stress of silty-sandy soils by using urease producing bacteria. American Scientific Research Journal for Engineering, Technology, and Sciences, 2018, 41(1): 271−277 (ASRJETS)
165. Zamani A, Montoya B M. Undrained monotonic shear response of MICP-treated silty sands. Journal of Geotechnical and Geoenvironmental Engineering, 2018, 144(6): 04018029
166. Khamehchiyan M, Rowshanbakht K, Nikudel M R, Sajedi R H. Biological improvement of sandy soil by microbial induced carbonate precipitation. Journal of Kerbala University, 2015: 100−110
167. Pakbaz M S, Behzadipour H, Ghezelbash G R. Evaluation of shear strength parameters of sandy soils upon microbial treatment. Geomicrobiology Journal, 2018, 35(8): 721−726
168. Hoang T, Alleman J, Cetin B, Choi S G. Engineering properties of biocementation coarse-and fine-grained sand catalyzed by bacterial cells and bacterial enzyme. Journal of Materials in Civil Engineering, 2020, 32(4): 04020030
169. Cui M J, Lai H J, Hoang T, Chu J. One-phase-low-pH enzyme induced carbonate precipitation (EICP) method for soil improvement. Acta Geotechnica, 2021, 16(2): 481−489
170. Mahawish A, Bouazza A, Gates W P. Improvement of coarse sand engineering properties by microbially induced calcite precipitation. Geomicrobiology Journal, 2018, 35(10): 887−897

171. Mahawish A, Bouazza A, Gates W P. Factors affecting the biocementing process of coarse sand. Proceedings of the Institution of Civil Engineers-Ground Improvement, 2019, 172(1): 25−36
172. Mahawish A, Bouazza A, Gates W P. Unconfined compressive strength and visualization of the microstructure of coarse sand subjected to different biocementation levels. Journal of Geotechnical and Geoenvironmental Engineering, 2019, 145(8): 04019033
173. Pan X, Chu J, Yang Y, Cheng L. A new biogrouting method for fine to coarse sand. Acta Geotechnica, 2020, 15(1): 1−16
174. Cui M J, Zheng J J, Chu J, Wu C C, Lai H J. Bio-mediated calcium carbonate precipitation and its effect on the shear behaviour of calcareous sand. Acta Geotechnica, 2021, 16(5): 1377−1389
175. Deng W, Wang Y. Investigating the factors affecting the properties of coral sand treated with microbially induced calcite precipitation. Advances in Civil Engineering, 2018, 2018: 9590653
176. Xiao P, Liu H, Stuedlein A W, Evans T M, Xiao Y. Effect of relative density and biocementation on cyclic response of calcareous sand. Canadian Geotechnical Journal, 2019, 56(12): 1849−1862
177. Xiao P, Liu H, Xiao Y, Stuedlein A W, Evans T M. Liquefaction resistance of bio-cemented calcareous sand. Soil Dynamics and Earthquake Engineering, 2018, 107: 9−19
178. Zhang X, Chen Y, Liu H, Zhang Z, Ding X. Performance evaluation of a MICP-treated calcareous sandy foundation using shake table tests. Soil Dynamics and Earthquake Engineering, 2020, 129: 105959
179. van der Star W R L, van Wijngaarden W K, van Paassen L A, van Baalen L R, Zwieten G. Stabilization of gravel deposits using microorganisms. In: Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering. Athens: Millpress, 2011
180. van Paassen L A, Hemert W J, Star W R L, Zwieten G V, Baalen L V. Direct shear strength of biologically cemented gravel. In: Proceedings of GeoCongress 2012. Oakland: American Society of Civil Engineers, 2012, 968–977
181. Mahawish A, Bouazza A, Gates W P. Effect of particle size distribution on the bio-cementation of coarse aggregates. Acta Geotechnica, 2018, 13(4): 1019−1025
182. Mahawish A, Bouazza A, Gates W P. Strengthening crushed coarse aggregates using bio-grouting. Geomechanics and Geoengineering, 2019, 14(1): 59−70
183. Wu C Z, Chu J, Cheng L, Wu S F. Biogrouting of aggregates using premixed injection method with or without pH adjustment. Journal of Materials in Civil Engineering, 2019, 31(9): 06019008
184. Gomez M G, DeJong J T. Engineering properties of biocementation improved sandy soils. In: Grouting 2017. Honolulu: American Society of Civil Engineers, 2017, 23–33
185. Phadnis H S, Santamarina J C. Bacteria in sediments: Pore size effects. Géotechnique Letters, 2011, 1(4): 91−93
186. Ma G, He X, Jiang X, Liu H, Chu J, Xiao Y. Strength and permeability of bentonite-assisted biocemented coarse sand. Canadian Geotechnical Journal, 2021, 58(7): 969−981
187. Wu C Z, Chu J. Biogrouting method for stronger bond strength for aggregates. Journal of Geotechnical and Geoenvironmental Engineering, 2020, 146(11): 06020021
188. Cheng L, Shahin M A. Urease active bioslurry: A novel soil improvement approach based on microbially induced carbonate precipitation. Canadian Geotechnical Journal, 2016, 53(9): 1376−1385
189. Amarakoon G G N N, Kawasaki S. Factors affecting the improvement of sand properties treated with microbially-induced calcite precipitation. In: Geo-Chicago 2016. Chicago: American Society of Civil Engineers, 2016, 72–83
190. Zhao Q, Li L, Li C, Li M, Amini F, Zhang H. Factors affecting improvement of engineering properties of MICP-treated soil catalyzed by bacteria and urease. Journal of Materials in Civil Engineering, 2014, 26(12): 04014094
191. Lin H, Suleiman M, Brown D, Kavazanjian E Jr. Mechanical behavior of sands treated by microbially induced carbonate precipitation. Journal of Geotechnical and Geoenvironmental Engineering, 2016, 142(2): 04015066
192. Terzis D, Laloui L. 3-D micro-architecture and mechanical response of soil cemented via microbial-induced calcite precipitation. Scientific Reports, 2018, 8(1): 1416
193. Terzis D, Laloui L. Cell-free soil bio-cementation with strength, dilatancy and fabric characterization. Acta Geotechnica, 2019, 14(3): 639−656
194. Dhami N K, Reddy M S, Mukherjee A. Significant indicators for biomineralisation in sand of varying grain sizes. Construction & Building Materials, 2016, 104: 198−207
195. Cheng L, Cord-Ruwisch R, Shahin M A. Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation. Canadian Geotechnical Journal, 2013, 50(1): 81−90
196. Eryürük K, Yang S, Suzuki D, Sakaguchi I, Akatsuka T, Tsuchiya T, Katayama A. Reducing hydraulic conductivity of porous media using $CaCO_3$ precipitation induced by *Sporosarcina pasteurii*. Journal of Bioscience and Bioengineering, 2015, 119(3): 331−336
197. Cardoso R, Pedreira R, Duarte S O D, Monteiro G A. About calcium carbonate precipitation on sand biocementation. Engineering Geology, 2020, 271: 105612
198. Zamani A, Montoya B M, Gabr M A. Investigating challenges of in situ delivery of microbial-induced calcium carbonate precipitation (MICP) in fine-grain sands and silty sand. Canadian Geotechnical Journal, 2019, 56(12): 1889−1900
199. Tsukamoto M, Oda K. Influence of relative density on microbial carbonate precipitation and mechanical properties of sand. In: Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering. Paris: Presses des Ponts, 2013, 2613–2616
200. Cheng L, Shahin M A, Cord-Ruwisch R, Addis M, Hartanto T, Elms C. Soil stabilisation by microbial-induced calcite precipitation (micp): Investigation into some physical and environmental aspects. In: 7th International Congress on Environmental Geotechnics: ICEG2014. Melbourne: Engineers Australia, 2014, 1105
201. Rowshanbakht K, Khamehchiyan M, Sajedi R H, Nikudel M R. Effect of injected bacterial suspension volume and relative density on carbonate precipitation resulting from microbial

treatment. Ecological Engineering, 2016, 89: 49−55

202. Lakshmi S M, Mathura J, Gayathri U, Vedhanayaghi V J. Enhancement of shear strength characteristics by microbial cementation in sand. International Journal of Innovative Research Explorer, 2019, 5(6): 1−11
203. Song C, Elsworth D, Zhi S, Wang C. The influence of particle morphology on microbially induced $CaCO_3$ clogging in granular media. Marine Georesources and Geotechnology, 2021, 39(1): 74−81
204. Gat D, Tsesarsky M, Wahanon A, Ronen Z. Ureolysis and MICP with model and native bacteria: Implications for treatment strategies. In: Proceedings of the 2014 Geo-Congress. Atlanta: American Society of Civil Engineers, 2014, 1713–1720
205. Hataf N, Baharifard A. Reducing soil permeability using microbial induced carbonate precipitation (MICP) method: A case study of shiraz landfill soil. Geomicrobiology Journal, 2020, 37(2): 147−158
206. Wen K, Li Y, Amini F, Li L. Impact of bacteria and urease concentration on precipitation kinetics and crystal morphology of calcium carbonate. Acta Geotechnica, 2020, 15(1): 17−27
207. Wang Y Z, Soga K, DeJong J T, Kabla A. Effects of bacterial density on growth rate and characteristics of microbial-induced CaCO3 precipitates: A particle-scale experimental study. Journal of Geotechnical and Geoenvironmental Engineering, 2021, 147(6): 04021036
208. Zhao Y, Fan C, Liu P, Fang H, Huang Z. Effect of activated carbon on microbial-induced calcium carbonate precipitation of sand. Environmental Earth Sciences, 2018, 77(17): 615
209. Omoregie A I, Palombo E A, Ong D E L, Nissom P M. A feasible scale-up production of *Sporosarcina pasteurii* using custom-built stirred tank reactor for *in-situ* soil biocementation. Biocatalysis and Agricultural Biotechnology, 2020, 24: 101544
210. Zhao Y, Xiao Z, Lv J, Shen W, Xu R. A novel approach to enhance the urease activity of *Sporosarcina pasteurii* and its application on microbial-induced calcium carbonate precipitation for sand. Geomicrobiology Journal, 2019, 36(9): 819−825
211. Achal V, Mukherjee A, Basu P C, Reddy M S. Strain improvement of *Sporosarcina pasteurii* for enhanced urease and calcite production. Journal of Industrial Microbiology & Biotechnology, 2009, 36(7): 981−988
212. Bu C, Wen K, Liu S, Ogbonnaya U, Li L. Development of bio-cemented constructional materials through microbial induced calcite precipitation. Materials and Structures, 2018, 51(1): 30
213. Inagaki Y, Tsukamoto M, Mori H, Sasaki T, Soga K, Al Qabany A, Hata T. The influence of injection conditions and soil types on soil improvement by microbial functions. In: Proceedings of Geo-Frontiers 2011. Dallas: American Society of Civil Engineers, 2011, 4021–4030
214. Li M, Wen K, Li Y, Zhu L. Impact of oxygen availability on microbially induced calcite precipitation (MICP) treatment. Geomicrobiology Journal, 2018, 35(1): 15−22
215. Mortensen B M, DeJong J T. Strength and stiffness of MICP treated sand subjected to various stress paths. In: Proceedings of Geo-Frontiers 2011. Dallas: American Society of Civil Engineers, 2011, 4012–4020
216. Park S S, Choi S G, Kim W J, Lee J C. Effect of microbially induced calcite precipitation on strength of cemented sand. New Frontiers in Geotechnical Engineering GSP, 2017, 243: 47−56
217. Terzis D, Bernier-Latmani R, Laloui L. Fabric characteristics and mechanical response of bio-improved sand to various treatment conditions. Géotechnique Letters, 2016, 6(1): 50−57
218. Chen H J, Huang Y H, Chen C C, Maity J P, Chen C Y. Microbial induced calcium carbonate precipitation (MICP) using pig urine as an alternative to industrial urea. Waste and Biomass Valorization, 2019, 10(10): 2887−2895
219. Achal V, Pan X. Influence of calcium sources on microbially induced calcium carbonate precipitation by Bacillus sp. CR2. Applied Biochemistry and Biotechnology, 2014, 173(1): 307−317
220. Gorospe C M, Han S H, Kim S G, Park J Y, Kang C H, Jeong J H, So J S. Effects of different calcium salts on calcium carbonate crystal formation by *Sporosarcina pasteurii* KCTC 3558. Biotechnology and Bioprocess Engineering; BBE, 2013, 18(5): 903−908
221. Zhang Y, Guo H X, Cheng X H. Role of calcium sources in the strength and microstructure of microbial mortar. Construction & Building Materials, 2015, 77: 160−167
222. Zhang Y, Guo H X, Cheng X H. Influences of calcium sources on microbially induced carbonate precipitation in porous media. Materials Research Innovations, 2014, 18(sup2): 79−84
223. Cheng L, Shahin M A, Cord-Ruwisch R. Bio-cementation of sandy soil using microbially induced carbonate precipitation for marine environments. Geotechnique, 2014, 64(12): 1010−1013
224. Liang S, Chen J, Niu J, Gong X, Feng D. Using recycled calcium sources to solidify sandy soil through microbial induced carbonate precipitation. Marine Georesources and Geotechnology, 2020, 38(4): 393−399
225. Liu L, Liu H, Xiao Y, Chu J, Xiao P, Wang Y. Biocementation of calcareous sand using soluble calcium derived from calcareous sand. Bulletin of Engineering Geology and the Environment, 2018, 77(4): 1781−1791
226. Al Qabany A, Soga K. Effect of chemical treatment used in MICP on engineering properties of cemented soils. Geotechnique, 2013, 63(4): 331−339
227. Lai H J, Cui M J, Wu S F, Yang Y, Chu J. Retarding effect of concentration of cementation solution on biocementation of soil. Acta Geotechnica, 2021, 16(5): 1457−1472
228. Mujah D, Cheng L, Shahin M A. Microstructural and geomechanical study on biocemented sand for optimization of MICP process. Journal of Materials in Civil Engineering, 2019, 31(4): 04019025
229. Velpuri N V P, Yu X, Lee H I, Chang W S. Influence factors for microbial-induced calcite precipitation in sands. In: Geo-China 2016. Shandong: American Society of Civil Engineers, 2016, 44–52
230. Mori D, Jyoti P, Thakur T, Masakapalli S K, Uday K V. Influence of cementing solution concentration on calcite precipitation pattern in biocementation. In: Advances in Computer Methods and Geomechanics. Singapore: Springer, 2020, 737–746
231. Wen K, Li Y, Liu S, Bu C, Li L. Development of an improved immersing method to enhance microbial induced calcite precipitation treated sandy soil through multiple treatments in low cementation media concentration. Geotechnical and Geological

Engineering, 2019, 37(2): 1015−1027

232. Li W, Chen W S, Zhou P P, Zhu S L, Yu L J. Influence of initial calcium ion concentration on the precipitation and crystal morphology of calcium carbonate induced by bacterial carbonic anhydrase. Chemical Engineering Journal, 2013, 218: 65−72

233. Okwadha G D O, Li J. Optimum conditions for microbial carbonate precipitation. Chemosphere, 2010, 81(9): 1143−1148

234. Cheng L, Shahin M A, Chu J. Soil bio-cementation using a new one-phase low-pH injection method. Acta Geotechnica, 2019, 14(3): 615−626

235. van Paassen L, Ghose R, van der Linden T, van der Star W, van Loosdrecht M. Quantifying biomediated ground improvement by ureolysis: Large-scale biogrout experiment. Journal of Geotechnical and Geoenvironmental Engineering, 2010, 136(12): 1721−1728

236. Whiffin V S, van Paassen L A, Harkes M P. Microbial carbonate precipitation as a soil improvement technique. Geomicrobiology Journal, 2007, 24(5): 417−423

237. Rong H, Qian C X, Li L. Study on microstructure and properties of sandstone cemented by microbe cement. Construction & Building Materials, 2012, 36: 687−694

238. Ghasemi P, Zamani A, Montoya B. The effect of chemical concentration on the strength and erodibility of MICP treated sands. In: Eighth International Conference on Case Histories in Geotechnical Engineering. Philadelphia: American Society of Civil Engineers, 2019, 241–249

239. Keykha H A, Asadi A, Zareian M. Environmental factors affecting the compressive strength of microbiologically induced calcite precipitation-treated soil. Geomicrobiology Journal, 2017, 34(10): 889−894

240. Li W, Chen W S, Zhou P P, Cao L, Yu L J. Influence of initial pH on the precipitation and crystal morphology of calcium carbonate induced by microbial carbonic anhydrase. Colloids and Surfaces. B, Biointerfaces, 2013, 102: 281−287

241. Seifan M, Samani A K, Berenjian A. New insights into the role of pH and aeration in the bacterial production of calcium carbonate ($CaCO_3$). Applied Microbiology and Biotechnology, 2017, 101(8): 3131−3142

242. Martinez B C, Barkouki T H, DeJong J D, Ginn T R. Upscaling of microbial induced calcite precipitation in 0.5 m columns: experimental and modeling results. In: Proceedings of Geo-Frontiers 2011. Dallas: American Society of Civil Engineers, 2011: 4049–4059

243. Rong H, Qian C, Li L. Influence of molding process on mechanical properties of sandstone cemented by microbe cement. Construction & Building Materials, 2012, 28(1): 238−243

244. Al Qabany A, Mortensen B, Martinez B, Soga K, DeJong J. Microbial carbonate precipitation: correlation of S-wave velocity with calcite precipitation. In: Proceedings of Geo-Frontiers 2011. Dallas: American Society of Civil Engineers, 2011, 3993–4001

245. Cheng L, Cord-Ruwisch R. In situ soil cementation with ureolytic bacteria by surface percolation. Ecological Engineering, 2012, 42: 64−72

246. Cui M J, Zheng J J, Zhang R J, Lai H J, Zhang J. Influence of cementation level on the strength behaviour of bio-cemented sand. Acta Geotechnica, 2017, 12(5): 971−986

247. Harkes M P, van Paassen L A, Booster J L, Whiffin V S, van Loosdrecht M C M. Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement. Ecological Engineering, 2010, 36(2): 112−117

248. Tian Z F, Tang X, Xiu Z L, Xue Z J. Effect of different biological solutions on microbially induced carbonate precipitation and reinforcement of sand. Marine Georesources and Geotechnology, 2020, 38(4): 450−460

249. Kalantary F, Kahani M. Optimization of the biological soil improvement procedure. International Journal of Environmental Science and Technology, 2019, 16(8): 4231−4240

250. Martinez B, DeJong J, Ginn T, Montoya B, Barkouki T, Hunt C, Tanyu B, Major D. Experimental optimization of microbial-induced carbonate precipitation for soil improvement. Journal of Geotechnical and Geoenvironmental Engineering, 2013, 139(4): 587−598

251. Cui M J, Zheng J J, Zhang R J, Lai H J. Soil bio-cementation using an improved 2-step injection method. Arabian Journal of Geosciences, 2020, 13(23): 1270

252. Al Qabany A, Soga K, Santamarina C. Factors affecting efficiency of microbially induced calcite precipitation. Journal of Geotechnical and Geoenvironmental Engineering, 2012, 138(8): 992−1001

253. Feng K, Montoya B M. Drained shear strength of MICP sand at varying cementation levels. In: Proceedings of the International Foundations Congress and Equipment Expo 2015. San Antonio: American Society of Civil Engineers, 2015, 2242–2251

254. Gao Y, Hang L, He J, Chu J. Mechanical behaviour of biocemented sands at various treatment levels and relative densities. Acta Geotechnica, 2019, 14(3): 697−707

255. Montoya B M, DeJong J T, Boulanger R W. Dynamic response of liquefiable sand improved by microbial-induced calcite precipitation. Geotechnique, 2013, 63(4): 302−312

256. Montoya B, DeJong J. Stress-strain behavior of sands cemented by microbially induced calcite precipitation. Journal of Geotechnical and Geoenvironmental Engineering, 2015, 141(6): 04015019

257. Mujah D, Shahin M, Cheng L. Performance of biocemented sand under various environmental conditions. In: XVIII Brazilian Conference on Soil Mechanics and Geotechnical Engineering The Sustainable Future of Brazil goes through our Minas COBRAMSEG 2016. Belo Horizonte: Minas Gerais, 2016, 19–22

258. Jiang N J, Yoshioka H, Yamamoto K, Soga K. Ureolytic activities of a urease-producing bacterium and purified urease enzyme in the anoxic condition: Implication for subseafloor sand production control by microbially induced carbonate precipitation (MICP). Ecological Engineering, 2016, 90: 96−104

259. Mortensen B M, Haber M J, DeJong J T, Caslake L F, Nelson D C. Effects of environmental factors on microbial induced calcium carbonate precipitation. Journal of Applied Microbiology, 2011, 111(2): 338−349

260. Cardoso R, Pedreira R, Duarte S, Monteiro G, Borges H, Flores-Colen I. Biocementation as rehabilitation technique of porous materials. In: Delgado JMPQ (ed) New Approaches to Building Pathology and Durability. Singapore: Springer Singapore, 2016, 99–120

261. Hata T, Tsukamoto M, Inagaki Y, Mori H, Kuwano R, Gourc J P. Evaluation of multiple soil improvement techniques based on microbial functions. In: Proceedings of Geo-Frontiers 2011. Dallas: American Society of Civil Engineers, 2011, 3945–3955
262. Zhang C, Dehoff K, Hess N, Oostrom M, Wietsma T W, Valocchi A J, Fouke B W, Werth C J. Pore-scale study of transverse mixing induced $CaCO_3$ precipitation and permeability reduction in a model subsurface sedimentary system. Environmental Science & Technology, 2010, 44(20): 7833−7838
263. Nemati M, Voordouw G. Modification of porous media permeability, using calcium carbonate produced enzymatically in situ. Enzyme and Microbial Technology, 2003, 33(5): 635−642
264. Yang Y, Chu J, Xiao Y, Liu H, Cheng L. Seepage control in sand using bioslurry. Construction & Building Materials, 2019, 212: 342−349
265. Feng K, Montoya B M. Quantifying level of microbial-induced cementation for cyclically loaded sand. Journal of Geotechnical and Geoenvironmental Engineering, 2017, 143(6): 06017005
266. Simatupang M, Okamura M. Liquefaction resistance of sand remediated with carbonate precipitation at different degrees of saturation during curing. Soil and Foundation, 2017, 57(4): 619−631
267. Darby K M, Hernandez G L, DeJong J T, Boulanger R W, Gomez M G, Wilson D W. Centrifuge model testing of liquefaction mitigation via microbially induced calcite precipitation. Journal of Geotechnical and Geoenvironmental Engineering, 2019, 145(10): 04019084
268. Mele L, Tian J T, Lirer S, Flora A, Koseki J. Liquefaction resistance of unsaturated sands: Experimental evidences and theoretical interpretation. Geotechnique, 2019, 69(6): 541−553
269. Montoya B M, DeJong J T, Boulanger R W, Wilson D W, Gerhard R, Ganchenko A, Chou J C. Liquefaction mitigation using microbial induced calcite precipitation. In: Proceedings of GeoCongress 2012. Oakland: American Society of Civil Engineers, 2012, 1918–1927
270. Zamani A, Montoya B M. Shearing and Hydraulic Behavior of MICP Treated Silty Sand. In: Geotechnical Frontiers 2017. Orlando: American Society of Civil Engineers, 290–299
271. Amaratunga A, Grozic J. On the undrained unloading behaviour of gassy sands. Canadian Geotechnical Journal, 2009, 46(11): 1267−1276
272. Fourie A B, Hofmann B A, Mikula R J, Lord E R F, Robertson P K. Partially saturated tailings sand below the phreatic surface. Geotechnique, 2001, 51(7): 577−585
273. Grozic J L, Robertson P, Morgenstern N. Cyclic liquefaction of loose gassy sand. Canadian Geotechnical Journal, 2000, 37(4): 843−856
274. He J, Chu J. Undrained responses of microbially desaturated sand under monotonic loading. Journal of Geotechnical and Geoenvironmental Engineering, 2014, 140(5): 04014003
275. Rebata-Landa V, Santamarina J C. Mechanical effects of biogenic nitrogen gas bubbles in soils. Journal of Geotechnical and Geoenvironmental Engineering, 2012, 138(2): 128−137
276. Wang L Y, van Paassen L A, Kavazanjian E Jr. Feasibility study on liquefaction mitigation of fraser river sediments by microbial induced desaturation and precipitation (MIDP). Geo-Congress, 2020, 2020: 121−131
277. Mirshekari M, Ghayoomi M. Centrifuge tests to assess seismic site response of partially saturated sand layers. Soil Dynamics and Earthquake Engineering, 2017, 94: 254−265
278. O'Donnell S T, Kavazanjian Jr E. The effect of desaturation on the static and cyclic mechanical response of dense sand. In: International Foundation Congress and Equipment Expo 2018. Orlando: American Society of Civil Engineers, 2018, 232–241
279. Okamura M, Soga Y. Effects of pore fluid compressibility on liquefaction resistance of partially saturated sand. Soil and Foundation, 2006, 46(5): 695−700
280. Wang L Y, van Paassen L A, Gao Y Q, He J, Gao Y F, Kim D. Laboratory tests on mitigation of soil liquefaction using microbial induced desaturation and precipitation. Geotechnical Testing Journal, 2021, 44(2): 520−534
281. Yang J, Savidis S, Roemer M. Evaluating liquefaction strength of partially saturated sand. Journal of Geotechnical and Geoenvironmental Engineering, 2004, 130(9): 975−979
282. Zhang B, Muraleetharan K K, Liu C. Liquefaction of Unsaturated Sands. International Journal of Geomechanics, 2016, 16(6): D4015002
283. He J, Chu J, Ivanov V. Remediation of liquefaction potential of sand using the biogas method. Geo-congress, 2013, 2013: 879−887
284. Wu S F. Mitigation of liquefaction hazards using the combined biodesaturation and bioclogging method. Dissertation for the Doctoral Degree. Iowa State University, Ames, 2015
285. Kavazanjian E Jr, O'Donnell S T. Mitigation of earthquake-induced liquefaction via microbial denitrification: A two-phase process. IFCEE 2015, 2286–2295
286. Nakano A. Microbe-induced desaturation of sand using pore pressure development via denitrification. Géotechnique Letters, 2018, 8(1): 1−4
287. Wang K, Chu J, Wu S, He J. Stress–strain behaviour of bio-desaturated sand under undrained monotonic and cyclic loading. Geotechnique, 2021, 71(6): 521−533
288. Hall C, Hernandez G, Darby K M, van Paassen L, Kavazanjian E, DeJong J, Wilson D. Centrifuge model testing of liquefaction mitigation via denitrification-induced desaturation. In: Proceedings of Geotechnical Earthquake Engineering and Soil Dynamics IV. Sacramento: American Society of Civil Engineers, 2018, 117–126
289. Pham V P, van Paassen L A, van der Star W R L, Heimovaara T J. Evaluating strategies to improve process efficiency of denitrification-based MICP. Journal of Geotechnical and Geoenvironmental Engineering, 2018, 144(8): 04018049
290. Filet A, Gadret J, Loygue M, Borel S. Biocalcis and its applications for the consolidation of sands. In: Proceedings of the Fourth International Conference on Grouting and Deep Mixing. New Orleans: American Society of Civil Engineers, 2012, 1767–1780
291. van Paassen L A, Harkes M P, van Zwieten G A, van der Zon W H, van der Star W R L, van Loosdrecht M C M. Scale up of BioGrout: A biological ground reinforcement method. In: Proceedings of the 17th international conference on soil mechanics and geotechnical engineering. Lansdale: IOS Press,

2009, 2328–2333

292. van Paassen L. Bio-mediated ground improvement: from laboratory experiment to pilot applications. In: Geo-Frontiers 2011: Advances in Geotechnical Engineering. Dallas: American Society of Civil Engineers, 2011, 4099–4108
293. Wu S F, Li B, Chu J. Large-scale model tests of biogrouting for sand and rock. Proceedings of the Institution of Civil Engineers—Ground Improvement, 2019: 1−10
294. Johnston C, Trefry M, Rayner J, Ragusa S, De Zoysa D, Davis G. In situ bioclogging for the confinement and remediation of groundwater hydrocarbon plumes. In: Proceedings of the 1999 contaminated site remediation conference. Fremantle: Centre for Groundwater Studies, 1999
295. Ross N, Bickerton G. Application of biobarriers for groundwater containment at fractured bedrock sites. Remediation Journal, 2002, 12(3): 5−21
296. Castegnier F, Ross N, Chapuis R P, Deschênes L, Samson R. Long-term persistence of a nutrient-starved biofilm in a limestone fracture. Water Research, 2006, 40(5): 925−934
297. Blauw M, Lambert J, Latil M N. Biosealing: A method for *in situ* sealing of leakages. In: Proceedings of the International Symposium on Ground Improvement Technologies and Case Histories. Singapore: Research Publishing Services, 2009
298. Lambert J, Novakowski K, Blauw M, Latil M, Knight L, Bayona L. Pamper bacteria, they will help us: application of biochemical mechanisms in geo-environmental engineering. In: GeoFlorida 2010: Advances in Analysis, Modeling & Design. Florida: American Society of Civil Engineers, 2010, 618–627
299. Cuthbert M O, McMillan L A, Handley-Sidhu S, Riley M S, Tobler D J, Phoenix V R. A field and modeling study of fractured rock permeability reduction using microbially induced calcite precipitation. Environmental Science & Technology, 2013, 47(23): 13637−13643
300. Phillips A J, Cunningham A B, Gerlach R, Hiebert R, Hwang C, Lomans B P, Westrich J, Mantilla C, Kirksey J, Esposito R, Spangler L. Fracture sealing with microbially-induced calcium carbonate precipitation: A field study. Environmental Science & Technology, 2016, 50(7): 4111−4117
301. Phillips A J, Troyer E, Hiebert R, Kirkland C, Gerlach R, Cunningham A B, Spangler L, Kirksey J, Rowe W, Esposito R. Enhancing wellbore cement integrity with microbially induced calcite precipitation (MICP): A field scale demonstration. Journal of Petroleum Science Engineering, 2018, 171: 1141−1148
302. Gomez M G, Martinez B C, DeJong J T, Hunt C E, deVlaming L A, Major D W, Dworatzek S M. Field-scale bio-cementation tests to improve sands. Proceedings of the Institution of Civil Engineers-Ground Improvement, 2015, 168(3): 206−216
303. Gomez M G, Anderson C M, Graddy C M R, DeJong J T, Nelson D C, Ginn T R. Large-scale comparison of bioaugmentation and biostimulation approaches for biocementation of sands. Journal of Geotechnical and Geoenvironmental Engineering, 2017, 143(5): 04016124
304. Gomez M G, DeJong J T, Anderson C M. Effect of bio-cementation on geophysical and cone penetration measurements in sands. Canadian Geotechnical Journal, 2018, 55(11): 1632−1646
305. Gomez M G, Graddy C M R, DeJong J T, Nelson D C. Biogeochemical changes during bio-cementation mediated by stimulated and augmented ureolytic microorganisms. Scientific Reports, 2019, 9(1): 11517
306. Omoregie A I, Palombo E A, Ong D E L, Nissom P M. Biocementation of sand by *Sporosarcina pasteurii* strain and technical-grade cementation reagents through surface percolation treatment method. Construction & Building Materials, 2019, 228: 116828
307. Omoregie A I, Ngu L H, Ong D E L, Nissom P M. Low-cost cultivation of *Sporosarcina pasteurii* strain in food-grade yeast extract medium for microbially induced carbonate precipitation (MICP) application. Biocatalysis and Agricultural Biotechnology, 2019, 17: 247−255
308. Kahani M, Kalantary F, Soudi M R, Pakdel L, Aghaalizadeh S. Optimization of cost effective culture medium for *Sporosarcina pasteurii* as biocementing agent using response surface methodology: Up cycling dairy waste and seawater. Journal of Cleaner Production, 2020, 253: 120022
309. Dilrukshi R A N, Nakashima K, Kawasaki S. Soil improvement using plant-derived urease-induced calcium carbonate precipitation. Soil and Foundation, 2018, 58(4): 894−910
310. Hamdan N, Kavazanjian E Jr. Enzyme-induced carbonate mineral precipitation for fugitive dust control. Geotechnique, 2016, 66(7): 546−555
311. Kavazanjian E Jr, Almajed A, Hamdan N. Bio-inspired soil improvement using EICP soil columns and soil nails. In: Grouting 2017. Honolulu: American Society of Civil Engineers, 2017, 13–22
312. Nafisi A, Safavizadeh S, Montoya B M. Influence of microbe and enzyme-induced treatments on cemented sand shear response. Journal of Geotechnical and Geoenvironmental Engineering, 2019, 145(9): 06019008
313. Gao Y, He J, Tang X, Chu J. Calcium carbonate precipitation catalyzed by soybean urease as an improvement method for fine-grained soil. Soil and Foundation, 2019, 59(5): 1631−1637
314. Nam I H, Chon C M, Jung K Y, Choi S G, Choi H, Park S S. Calcite precipitation by ureolytic plant (*Canavalia ensiformis*) extracts as effective biomaterials. KSCE Journal of Civil Engineering, 2015, 19(6): 1620−1625
315. Park S S, Choi S G, Nam I H. Effect of plant-induced calcite precipitation on the strength of sand. Journal of Materials in Civil Engineering, 2014, 26(8): 06014017
316. Dilrukshi R A N, Watanabe J, Kawasaki S. Strengthening of sand cemented with calcium phosphate compounds using plant-derived urease. International Journal of Geomate, 2016, 11(25): 2461−2467
317. Pham V P, Nakano A, van der Star W R L, Heimovaara T J, van Paassen L A. Applying MICP by denitrification in soils: a process analysis. Environmental Geotechnics, 2018, 5(2): 79−93