Research Article

Mechanical Behavior and Microstructural Study of Biocemented Sand under Various Treatment Methods

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Biocementation mainly relies on the formation of calcium carbonate to bind soil particles. This paper investigates the effectiveness of biocementation in terms of treatment methods. The previously established two-phase methods are compared with newly developed one-phase-low-pH methods on their mechanical behavior and microstructure. The one-phase-low-pH methods present a higher urease fixation rate than two-phase methods, highlighting the cost-effectiveness of this method. A modified one-phase-low-pH using CH₃COOH is also compared with HCl-based one-phase-low-pH method. The results show that the morphology and size of precipitated crystals have a great influence on strength development. An optimized treatment method based on the one-phase-low-pH method is also established, which is accomplished via the injection of 5 U/ml of bacterial culture together with 2 M of cementation solution during each treatment. After four times of treatments, a total of 7% cumulative calcium carbonate content can be obtained with an unconfined compressive strength of 2.15 MPa.

1. Introduction

Soil improvement is an important part of geotechnical engineering [1]. Soil improvement is aimed at improving the engineering properties such as shear strength, compressibility, or permeability of weak soil. Inadequate soil improvement can cause many catastrophic geo-hazards, such as soil erosion, slope failure, soil liquefaction, water seepage, or flooding [2]. A wide range of soil improvement techniques has been developed and applied to satisfy various engineering requirements for construction. One of the most conventional soil improvement techniques is to use Portland cement such as cement grouting or deep cement mixing [3, 4]. Considering the substantial amount of energy is required for cement production or soil cement mixing and about 5-7% of total global anthropogenic carbon dioxide emission comes from the production of Portland cement [5–7], it is necessary to develop methods to use alternative binders with lower energy requirements and CO2 emissions [8, 9]. This is particularly the case in geotechnical engineering where a great amount of binders is normally consumed for soil improvement.

In recent years, studies on the use of microbially induced carbonate precipitation (MICP) process to improve the mechanical properties of soil as a substitute of cement for soil improvement have gained overwhelming attention, and this approach has been studied by many researchers [10–14]. Most studies focused mainly on the improvement of shear strength [15, 16] and the reduction of permeability [17–19] so far. Apart from sulphate reducing bacteria [20] and denitrifying bacteria [21], MICP via urea hydrolysis of urease-producing bacteria is the most widely researched
method for calcium carbonate precipitation. During the MICP process, urease catalyzes the hydrolysis of urea to produce carbamic acid and ammonia (Equation (1)). The carbamic acid is unstable, which rapidly decomposes to yield carbon dioxide and another molecule of ammonia [22, 23]. In solution, the released two molecules of ammonia and one molecule of carbon dioxide consequently equilibrate with their deprotonated and protonated forms, leading to the rise of pH [24] and enabling the calcium carbonate precipitation in the presence of soluble calcium ions (Equation (2)).

\[
\text{CO(NH}_2\text{)}_2 + 2\text{H}_2\text{O} \xrightarrow{\text{urease}} 2\text{NH}_4^+ + \text{CO}_3^{2-} \quad (1)
\]

\[
\text{CO}_3^{2-} + \text{Ca}^{2+} \rightarrow \text{CaCO}_3 \downarrow \quad (2)
\]

The precipitated calcium carbonate crystals can bond sand particles and thus increase the strength of the soil. In addition to strength development, the permeability of the soil will be reduced because the calcium carbonate crystals also fill in the pores of the sand [19]. However, the current applications of this technique for soil improvement have been restricted to lab scales due to the requirement of repetitive treatments [25], high cost [26], nonuniformity in treatment [13], and undesirable ammonia emissions [27]. One of the biggest obstacles of the MICP technique is its effectiveness among the aforementioned limitations. As such, several treatment methods are reported to favor the effectiveness of treatment using MICP for soil improvement.

The most commonly used is the two-phase method [28]. In this method, the bacterial culture is injected first followed by the injection of cementation solution. This two-phase method can avoid the rapid flocculation/bioflocs and clogging of pore voids at the injection point, which impedes further treatment. The bioflocs refer to the initial coagulation of bacterial cells induced by a trace amount of calcium ions [13]. However, the bacterial culture can be flushed out by the subsequent injection of cementation solution, resulting in a poor bacteria fixation rate. Cheng and Cord-Ruwisch [29] proposed a percolation method to improve the conventional two-phase method, which is the so-called staged injection method. Unlike the conventional two-phase method, an interval between the injection of bacterial culture and cementation solution is created, which applies a retention period to allow bacteria to be better fixed within the soil matrix, avoiding the accumulation of calcium carbonate crystals near the injection end and thus improving the overall uniformity of the distributed calcium carbonate precipitation [30]. Although this method can increase the bacteria fixation rate, it still leads to a waste of bacteria due to the flushing of subsequent injection of cementation solution. Recently, Cheng et al. [13] introduced a novel one-phase injection method using the one-phase-low-pH biocementation solution. This one-phase-low-pH biocementation solution is obtained by mixing pH adjusted bacterial culture with cementation solution (urea and CaCl₂). As a result, the bacteria can be fixed into sand matrix due to the instant urea hydrolysis process. The one-phase-low-pH method can also prevent the quick interaction between the bacterial cells and cementation solution, avoiding rapid clogging of pore voids and facilitating subsequent treatments. Consequently, it improves the effectiveness of MICP as the bacteria is fixed into the soil matrix associated with instant bioincementation. Therefore, making the MICP technique more effective to facilitate field application is prevailing. Although the one-phase-low-pH would in theory avoid the formation of bioflocs and improve the uniformity of bioincementation, the study on the effectiveness of different biotreatment methods has not investigated yet.

This paper is aimed at comparing the effectiveness via mechanical behavior and microstructure of biocemented sand under different treatment methods. These methods include the two-phase method, staged two-phase method, and HCl buffered one-phase method. In this study, H₂COOH was also tried to reduce pH in the biocementation solution. Several parameters related to the effectiveness of MICP process under various treatment methods were examined and discussed, including the bacteria fixation rate, urease activity, and unconfined compressive strength.

2. Materials and Methods

2.1. Bacterial Culture and Cementation Solution. The screened pure culture was selected for biocementation test as reported in the previous study [31]. The concentration of bacteria was determined by measuring the optical density at a wavelength of 600 nm (OD600) using spectrophotometry [13]. The bacteria activity was checked by mixing 10 ml of 3 M of urea solution, 8 ml of deionized water, and 2 ml of bacteria solution, followed by measuring the conductivity at every 1 min interval until 4 readings were obtained. The difference between the first and last readings was calculated, and an average number of 4 readings was recorded as the conductivity of bacteria. Conductivity is converted to urease activity by the following conversion rate of 1 ms/min = 111 U/ml [32]. The optical density (OD600) of harvested bacterial culture varied between 2 and 2.5, and the urease activity was approximately 20 U/ml (1 U = 1 μmol urea hydrolyzed per minute). The pH value of the final harvested bacterial culture was around 8.2 measured by pH meter. The cementation solution consisted of 2 M of equimolar of CaCl₂ and urea.

2.2. Urease Fixation Rate of Various Treatment Method. A total of 8 identical short acrylic sand columns (4 groups) were filled with 400 g of dry Ottawa sand (D₅₀ = 0.4 mm, specified by ASTM C788) with a void volume of 90 cm³. The initial urease used for each column was 250 U, and the urease from effluent was measured and compared with the initial urease to determine the urease fixation rate of each method. The details of the four different treatment methods applied to investigate the urease fixation rate are listed in Table 1.

2.3. Effect of Treatment Methods on Strength Development. The most commonly used two-phase method with different initial urease activity at first injection and different acidified
one-phase methods with HCl and CH₃COOH were compared. The screened pure culture was used as a bacteria source, and other conditions are consistent as shown in Table 2. It should be noted that using the one-phase method needs to mix bacterial culture and cementation solution, the volume of bacteria and cementation solution of the one-phase method is the same as the two-phase method after mixing in spite of the volume of solvent. The treatment process of the one-phase method was carried out by mixing the bacterial culture and cementation solution, followed by simple percolation, as presented in Figure 1. The two-phase method was conducted in two strategies. One was to inject half volume (45 ml) of 5 U/ml bacterial culture, followed by the injection of half volume of cementation solution (45 ml) over a half-hour time interval. The injection time duration could ensure the bacteria cells fixate onto the sand grains. After injecting half of the 2 M of cementation solution, the final concentration was considered as 1 M. In this strategy, bacterial culture was injected during each treatment. Another strategy was to inject half volume of higher urease activity at 20 U/ml, followed by another half volume of cementation solution after a half-hour. The subsequent treatment was carried out by injecting 90 ml of cementation solution only with a concentration of 1 M, which showed the

| Amount of bacteria injected (ml) | HCl-based one-phase-low-pH method | CH₃COOH-based one-phase-low-pH method | Staged two-phase method | Two-phase method |
|---------------------------------|----------------------------------|--------------------------------------|------------------------|-----------------|
| Urease activity (U)             | 5                                | 5                                    | 5                      | 2.5             |
| Total urease before injection (U) | 250                             | 250                                  | 250                    | 250             |
| Amount of injected CS (ml)      | 50                               | 50                                   | 50                     | 100             |
| Concentration of CS (M)         | 2                                | 2                                    | 2                      | 1               |

| Treatment method | Treatment strategy | Treatment conditions | Rounds of treatment |
|------------------|--------------------|----------------------|---------------------|
| HCl-based one-phase method | Premix 50 ml of pH adjusted BC with 50 ml of CS, followed by injection of 100 ml mixture | 5 U/ml, 45 ml | 4 |
| CH₃COOH-based one-phase method | Premix 50 ml of pH adjusted BC with 50 ml CS, followed by injection of 100 ml mixture | 5 U/ml, 45 ml | 4 |
| Two-phase method | Inject 50 ml (half void volume) of BC, followed by injection of 50 ml of CS in half an hour interval | 2 M, 45 ml | 4 |
| Two-phase method | Inject 100 ml (one void volume) of BC, followed by injection of 100 ml of CS in half an hour interval | 2 M, 45 ml | 4 |

BC: bacterial culture; CS: cementation solution.

Table 2: Biocementation with different treatment methods.
same amount of cementation agents as 2 M of 45 ml. The initial pH of all one-phase methods was set at 6 [33].

2.4. Optimal Treatment of the One-Phase-Low-pH Method.

To investigate the optimal treatment method, 48 identical short transparent acrylic sand columns (internal diameter = 50 mm and length = 100 mm) were prepared to evaluate the proposed one-phase-low-pH method. A total of 400 g of dry Ottawa sand was packed into short sand columns in three consecutive layers, ensuring a void volume of 90 cm$^3$ for each column to maintain consistency between tests. A detailed experimental program for this series of tests is presented in Table 3. Before the biotreatment, the all-in-one solution with initial pH of 6 was prepared using HCl. During the first treatment, 100 ml (1.1 times of void volume) of the all-in-one solution was percolated into the sand column. Repeated treatment (injecting the mixture of bacterial culture and cementation solution or only the cementation solution) was applied every 24 hours by following Table 3 to reach a satisfying level of cementation.

2.5. Residual Calcium Content, Strength, Calcium Carbonate Content, and Microstructure.

The residual calcium content was measured by following the EDTA method as stated before [18]. After treatment, unconfined compression tests were conducted on the treated sand columns, followed by the calcium carbonate content determination using the acid-washing and rinsing method [34] to reveal the cementation level of biocemented sand. All measurements were carried out in triplicate, and average values were reported unless otherwise stated. Scanning Electron Microscopy (SEM, Zeiss EV050, UK) observations were also carried out to image the morphologies of the precipitated calcium carbonate, which is important to study the mechanical properties of biocemented sand in detail. Microstructural specimens were obtained from crushed biocemented samples. All specimens were rinsed with tap water and oven-dried at 105° C for 24 h prior to microstructural tests.

### Table 3: Detailed testing program of sand column tests.

| Test # | Urease activity (U/ml) | Initial pH | 1st treatment | 2nd treatment | 3rd treatment | 4th treatment |
|--------|-----------------------|------------|---------------|---------------|---------------|--------------|
| 1      | 2.5                   | 6          | BC+2M CS      | BC+2M CS      | BC+2M CS      | BC+2M CS     |
| 2      | 5                     | 6          | BC+2M CS      | BC+2M CS      | BC+2M CS      | BC+2M CS     |
| 3      | 7.5                   | 6          | BC+2M CS      | BC+2M CS      | BC+2M CS      | BC+2M CS     |
| 4      | 10                    | 6          | BC+2M CS      | BC+2M CS      | BC+2M CS      | BC+2M CS     |
| 5      | 15                    | 6          | BC+2M CS      | BC+2M CS      | BC+2M CS      | BC+2M CS     |
| 6      | 20                    | 6          | BC+2M CS      | BC+2M CS      | BC+2M CS      | BC+2M CS     |
| 7      | 2.5                   | 6          | BC+2M CS      | 1M CS         | 1M CS         | 1M CS        |
| 8      | 5                     | 6          | BC+2M CS      | 1M CS         | 1M CS         | 1M CS        |
| 9      | 7.5                   | 6          | BC+2M CS      | 1M CS         | 1M CS         | 1M CS        |
| 10     | 10                    | 6          | BC+2M CS      | 1M CS         | 1M CS         | 1M CS        |
| 11     | 15                    | 6          | BC+2M CS      | 1M CS         | 1M CS         | 1M CS        |
| 12     | 20                    | 6          | BC+2M CS      | 1M CS         | 1M CS         | 1M CS        |

BC: bacterial culture; CS: cementation solution.

3. Results and Discussion

3.1. Urease Fixation Rate Using Different Treatment Methods.

The urease fixation rate under various treatment methods is presented in Figure 2, which shows that the one-phase-low-pH method using both acidic buffers has a higher urease fixation rate than the two-phase method. The one-phase-low-pH method can maintain a high urease fixation rate above 90%; this is attributed to the one-phase-low-pH method that can fix the bacteria within the sand matrix. The staged two-phase method also can attract a high urease fixation rate at 80% due to the retention period to allow better bacteria fixation; a similar observation was made by Cheng and Cord-Ruwisch [29]. However, the conventional two-phase method leads to a low urease fixation rate of 20%; this is because bacteria are not fixed but flushed out during the injection of cementation solution. Therefore, the one-phase-low-pH method for biocementation is considered as a material-saving and efficient treatment method than the previously reported two-phase method.

3.2. Mechanical Behavior of Biocemented Sand under Various Treatment Methods.

According to Figure 3, both one-phase methods indicated higher unconfined compressive strength than those samples treated by two-phase methods. This can be explained by the lower urease fixation rate of the two-phase method as stated above, consequently resulting in a lower calcium carbonate content so as to unconfined compressive strength. It was also found that the strength of biocemented sand using CH$_3$COOH-based one-phase method was lower than the HCl-based one-phase method with a variance of about 20-25%. This might be due to two factors: one is that the CH$_3$COOH could provide more H$^+$ than HCl at the same pH value, which led to the bacteria being subjected to severe pH conditions and affected the subsequent MICP process. When bacteria were affected by the severe condition, the ability of bacteria to precipitate calcium carbonate and the urease activity might also be affected, thus limiting the smaller crystal growth to a
larger size [35, 36]. This was likely because unaffected bacteria cells would provide better nucleation sites in the soil matrix than the affected one due to the severe pH condition; this led to the competition of crystals growth which was evident by the formation of numerous small crystals that could not grow larger. This agrees with the previous finding reported by Gandhi et al. [37] and Wang et al. [35], who have stated that the competition would occur if the nucleation of new crystals triumphs over the growth rate of the existing ones.

Another factor that needs to consider is that the spherical crystals after modification by organic acetate are spherical-shaped vaterite (Figure 4(b)), which is metastable and less effective in strength development than the rhombohedral-shaped calcite (Figure 4(a)). It is noteworthy that all crystals induced by the CH₃COOH-based one-phase-low-pH method were spherical. This is because CH₃COOH, an organic additive, can affect calcium carbonate morphologies by altering the calcite nucleation and growth processes, which has been evidenced by Meldrum and Hyde [38] and Konopacka-Lyskawa [39]. Similar observations have been reported by many researchers [40–42]. On the other hand, some coated crystals were found within biocemented sand as they were not precipitated at contact points but onto the surface only. Those coated crystals were randomly distributed rather than in the position of contact points. This kind of coated crystal was inefficient on strength development but might be useful for permeability reduction.

The most commonly used two-phase method was compared to the one-phase method regarding their, as well as the associated strength development. As can be seen in Figure 4, the SEM image depicted that major crystals precipitated between sand particles, bonding them together and contributing to strength improvement while forming a firm solid. This is the outcome of contact cementing instead of grain coating that contributes more to permeability reduction instead of gaining strength. A similar observation was made by Lin et al. [43]. The microstructural characteristics of the two-phase method are presented in Figures 4(c) and 4(d). The first pattern was the one treated with the injection of 5 U/ml bacterial culture during each treatment, as shown in Figure 4(c), while another one was treated with the injection of 20 U/ml bacterial culture at first treatment followed by injection of cementation solution only, which is presented in Figure 4(d). It can be seen from both Figure 4(c) and Figure 4(d) that all crystals induced by the two-phase method were typical clustered rhombohedral-shaped calcite. However, these crystals under both patterns showed a slight difference with the cluster of rhombohedral-shaped calcite induced by the one-phase method. In Figure 4(a), it was
Figure 4: SEM of calcium carbonate crystals induced by screened pure culture with various treatment methods at same magnification: (a) HCl-based one-phase method; (b) CH₃COOH-based one-phase method; (c) two-phase method with the injection of 5 U/ml bacterial culture during each treatment; (d) two-phase method with the injection of 20 U/ml bacterial culture at the first treatment only.

Figure 5: Correlation of calcium conversion efficiency and calcium carbonate content under different urease activity with four times of treatment through the method of BC + CS during each treatment.
observed that the clustered crystals obtained from the one-phased method were acute rhombohedra; however, the clustered calcite using the two-phase method was obtuse rhombohedra. In addition to rhombohedral shape, a few spherical crystals were also observed when the biocemented sand was injected with 20 U/ml bacterial culture at first treatment without the subsequent supply of bacterial culture. This was because the initial form of precipitated calcium carbonate was vaterite; however, the transformation would occur with more rounds of treatment up to four times, converting the primary spherical-shaped metastable vaterite into the more stable secondary rhombohedral-shaped calcite. This finding is in line with the transition phase reported by Terzis et al. [44] and Mujah et al. [40], who have reported that bacteria attached onto the surface of sand grains facilitated the formation of a nucleation site for the birth of calcium carbonate crystals within the sol matrix, and the subsequent treatment encouraged the transformation of calcium carbonate into a more stable polymorph.

3.3. Comparison of One-Time Injection of All-in-One Solution and Multiple Injections of the All-in-One Solution. The approach used to assess the optimal treatment method was to produce a cost-effective biocement by comparing the one-time injection of the all-in-one solution and multiple injections of the all-in-one solution. Figures 5 and 6 show the correlation of unconfinned compressive strength and calcium conversion efficiency (percentage of calcium ions converted to calcium carbonate) under different urease activity using the HCl-based all-in-all solution with an initial pH of 6. According to Figure 5, the results showed that BC + CS during each treatment could obtain high calcium conversion efficiency and high calcium carbonate content with the urease activity of 5 and 7.5 U/ml. Both urease activities could reach about 90% of calcium conversion efficiency during each treatment, and a total of 7.5% cumulative calcium carbonate content after four treatments could be cumulated with an unconfined compressive strength of 2.3 MPa at urease activity of 7.5 U/ml (Figure 6). In comparison, the 5 U/ml achieved a strength of 2.15 MPa with 7% calcium carbonate content. Overall, the unconfined compressive strength aligned with the calcium carbonate content which is similar to previous results [45]. Although higher urease activity (>7.5 U) was able to reach greater than 90% of calcium conversion efficiency in the first two treatments, the difference in chemical conversion rate was less than 10%. However, a dramatic calcium conversion efficiency decrease was observed at higher urease of 20 U/ml in the following two rounds of treatment, which resulted in lower calcium carbonate content of biocemented sand. One possible reason is that high urease activity leads to fast precipitation and a large amount of small size (1-10 μm in size) crystals (Figure 7), which fills out a great space within the sand matrix and influences the following treatments, creating locally clogged zones and reducing the mobile pore volume.
This reduced the pore space among sand particles and interfered with the subsequent precipitation, resulting in a lower unconfined compressive strength, as discussed by Van Paasen [46]. Although 5 U/ml did not obtain the highest strength, it was taken as the most cost-effective one. Therefore, 5 U/ml was considered the urease activity for the production of cost-effective and high-performance biocementation via the one-phase-low-pH method.

For the method of one-time injection of BC + CS and supply CS only in the following treatment, it was clear that both calcium carbonate content and unconfined compressive strength increased as the urease activity varied from 2.5 to 20 U/ml. For the low urease activity of 2.5 U/ml, only about 50% of calcium ions were converted into calcium carbonate in the first treatment, and the conversion rate dropped to 20% after the second treatment (Figure 8). Furthermore, the high urease activity of 20 U/ml obtained a high conversion rate of about 90% in the first two treatments; however, the conversion rate dropped to 57% with the third treatment and dropped further with the fourth treatment (Figure 8). This is because the residual bacteria is insufficient to convert all newly supplied calcium ions into calcium carbonate without the additional injection of bacterial culture. Similarly, high urease activity also impeded the subsequent calcium conversion efficiency the same as previous results so as to affect the chemical conversion efficiency of the one-phase-low-pH method. This is because of the creation of a local clogged zone where fast precipitation of a great number of small crystals occurs with higher urease activity. In terms of cost-effectiveness to produce biocementation,

**Figure 8:** Correlation of calcium conversion efficiency and calcium carbonate content under different urease activity through the method of one time injection of BC + CS followed by three times injection of 1 M of CS during each following treatment.

**Figure 9:** Correlation of unconfined compressive strength and calcium carbonate content under different urease activity through the method of one time injection of BC + CS followed by three times injection of 1 M of CS during each following treatment.
one-time injection of BC + CS with 20 U/ml followed by
three times injection of CS was the same as the method of
four times of injection of BC + CS with 5 U/ml other than
the water usage as 20 U/ml of bacterial culture need dilute
four times to be 5 U/ml. However, the construction time
and cost of using urease activity of 20 U/ml are slightly lower
since pH only needs to be adjusted one time. By comparison,
the unconfined compressive strength could reach 1.5 MPa
for one time injection of BC + CS with 20 U/ml (Figure 9).
This was significantly lower than the 2.15 MPa obtained by
four times the injection of BC + CS with 5 U/ml.

4. Conclusions

This study presented a comparison of the mechanical behav-
ior and microstructure study of biocemented sand under
various treatment methods. A modified CH3COOH-based
one-phase-low-pH injection method was also investigated
and compared with the previously established one-phase-
low-pH method using HCl. The two-phase methods were
then compared with the one-phase-low-pH methods in
terms of their strength and crystal morphology. A higher
urease fixation rate was achieved by the one-phase-low-pH
injection method compared with the two-phase methods,
suggesting a saving in the cementation material and the
effectiveness of the one-phase-low-pH injection method.
An optimized one-phase-low-pH treatment strategy was
also developed, the combination of BC + CS with urease
activity of 5 U/ml and 2 M of cementation solution during
each treatment was proved to be the most efficient treatment
protocol, achieved an unconfined compressive strength of
2.15 MPa with 7% of calcium carbonate content. The devel-
oped formulation provides a more cost-effective treatment
method to make biocement as a promising candidate for soil
improvement. Other parameters, such as uniformity and
cost, have not been reported in this study, and they are
worthwhile to carry out in future studies.

Data Availability

The datasets and materials used and/or analyzed during the
current study are available from the corresponding author
on reasonable request.

Conflicts of Interest

The authors declare that they have no known competing
financial interests or personal relationships that could have
appeared to influence the work reported in this paper.

Authors’ Contributions

Xuecheng Gao contributed to the conceptualization, meth-
odology, formal analysis, investigation, data curation, and
writing—original draft. Shaokang Han contributed to the
methodology, investigation, and data curation. Yang Yang
contributed to the conceptualization, methodology, valida-
tion, resources, writing—review and editing, and funding
acquisition. Wengang Zhang contributed to the validation
and writing—review and editing. Tan Zou contributed to
the methodology, investigation, and data curation. Liang
Cheng contributed to the conceptualization, validation, and
data curation. Yang Yang contributed to the conceptualiza-
tion, methodology, validation, and writing—review and editing.

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References

[1] B. Yuan, Z. Li, Y. Chen et al., “Mechanical and microstructural
properties of recycling granite residual soil reinforced with
glass fiber and liquid-modified polyvinyl alcohol polymer,”
Chemosphere, vol. 286, no. 1, article 131652, 2022.
[2] M. Gaafer, H. Bassioni, and T. Mostafa, “Soil improvement
techniques,” International Journal of Scientific & Engineering
Research, vol. 6, no. 12, pp. 217–222, 2015.
[3] S. I. Haralambos, “Compressive strength of soil improved with
cement, in contemporary topics in ground modification, prob-
lem soils,” Contemporary Topics in Ground Modification, Problem Soils, and Geo-Support, pp. 289–296, 2009.
[4] A. Al-Tabbaa, “Soil mixing in the UK 1991–2001: state of prac-
tice report,” Proceedings of the Institution of Civil Engineers-
Ground Improvement, vol. 7, no. 3, pp. 117–126, 2003.
[5] E. Benhelal, G. Zahedi, E. Shamsaei, and A. Bahadori, “Global
strategies and potentials to curb CO2 emissions in cement
industry,” Journal of Cleaner Production, vol. 51, pp. 142–161, 2013.
[6] S. Ruan, J. Qiu, Y. Weng et al., “The use of microbial induced
carbonate precipitation in healing cracks within reactive mag-
nesia cement-based blends,” Cement and Concrete Research,
vol. 115, pp. 176–188, 2019.
[7] C. Unluer and A. Al-Tabbaa, “Impact of hydrated magnesium
carbonate additives on the carbonation of reactive MgO
cements,” Cement and Concrete Research, vol. 54, pp. 87–97,
2013.
[8] D. Zhang, M. A. Shahin, Y. Yang, H. Liu, and L. Cheng, “Effect
of microbially induced calcite precipitation treatment on the
bonding properties of steel fiber in ultra-high performance
cement concrete,” Engineering, vol. 50, article 104132, 2022.
[9] Y. Yang, S. Ruan, S. Wu et al., “Biocarbonation of reactive
calcite precipitation treatment on the bonding properties of
magnesia cement-based blends,” Acta Geotechnica, vol. 16,
no. 4, pp. 1113–1125, 2021.
[10] V. S. Whiffin, Microbial CaCO3 precipitation for the produc-
tion of biocement, Murdoch University, 2004.
[11] J. De Jong, K. Soga, E. Kavazanjian et al., “Biogeochemical pro-
cesses and geotechnical applications: progress, opportunities
and challenges,” Geotechnique, vol. 63, no. 4, pp. 287–301,
2013.
[12] V. Ivanov and J. Chu, “Applications of microorganisms to geo-
technical engineering for bioclogging and biocementation of
soil in situ,” Reviews in Environmental Science and Bio/Technol-
ogy, vol. 7, no. 2, pp. 139–153, 2008.
various treatment conditions,” *Géotechnique Letters*, vol. 6, no. 1, pp. 50–57, 2016.

[45] J. Chu, V. Stabnikov, and V. Ivanov, “Microbially induced calcium carbonate precipitation on surface or in the bulk of soil,” *Geomicrobiology Journal*, vol. 29, no. 6, pp. 544–549, 2012.

[46] L. A. Van Paassen, *Biogrout, Ground Improvement by Microbial Induced Carbonate Precipitation*, Delft University of Technology, 2009.