

Laboratory and Model-Scale Investigation of Biocementation Effects on Sand Behavior and Foundation Bearing Capacity

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ABSTRACT: Microbially Induced Calcite Precipitation (MICP) through urea hydrolysis is one of the widely investigated biological soil improvement methods, which harnesses the metabolism of ureolytic bacteria to catalyze calcite precipitation in the soil environment. The precipitated calcite enhances subsequently the stiffness of soils by forming bridges between soil grains. Although laboratory studies have shown promising results, natural soils vary widely in their properties across different areas, and these variations may strongly affect treatment efficiency. To investigate such effects, element-scale experiments were performed on three sandy soils with different mean grain sizes but similar coefficients of uniformity. All samples were treated under the same conditions, and their mechanical behavior was examined by drained monotonic triaxial tests along with calcite content measurements. This setup allowed for the isolation of the mean grain size effect on both the MICP process and the posttreatment mechanical behavior of the soils. Subsequently, model-scale experiments were performed in a 56 cm×36 cm×30 cm treatment box filled with one of the sands from the element-scale experiments. A 4×4×1.5 cm model foundation was placed at that soil surface to assess the effect of the MICP method on its load-settlement response. The small-scale experiments showed that a varying range of calcite contents, stiffness, and shear strength can be obtained depending on the mean grain size of the sands. At larger scale, the injection strategy influenced the spatial distribution of calcite precipitation, while foundation tests confirmed an improved load-bearing capacity and reduced settlements after treatment. Importantly, isolating the effects of parameters such as mean grain size provides clearer insight into the governing mechanisms of biocementation, enabling more reliable predictions of MICP performance based on initial soil characteristics and supporting more reliable prediction and design of future MICP applications.

KEYWORDS: biocementation, triaxial tests, model box tests, load settlement curves

1 INTRODUCTION

Among different biomediated soil improvement methods, Microbially Induced Calcite Precipitation (MICP) via urea hydrolysis has received significant attention in the recent past. In this process, the urease enzyme produced by ureolytic bacteria increases the rate of urea hydrolysis by as much as 10^{14} times faster than the natural degradation process (Estiu and Merz, 2004). The carbonate ions generated through the hydrolysis process subsequently react with the provided calcium ions to form calcite. The precipitated calcite forms bridges between soil grains and/or reduces pore space, leading to improved strength and stiffness in the treated soils. MICP-based biocementation is mostly effective in sandy soils, where the pore throat geometry is suitably compatible with bacterial cell sizes, enabling sufficient bacterial transport. Fine-grained soils, by contrast, exhibit pronounced size incompatibility, which constrains the free movement of the bacterial cells (Mitchell and Santamarina, 2005). As a result, cell accumulation occurs near injection points due to the filtration of the cells by soil pore throat. These effects collectively lead to spatial heterogeneity in calcite distribution along the treatment zone. To mitigate the cell transport limitations in fine-grained soils, the mixing method has been proposed as a potential alternative to solution injection, whereby bacteria and/or cementation reagents are blended directly with the soil prior to compaction (Soon et al., 2014). Although this method enhances the uniformity of the bacterial cell and calcite distribution, it disturbs the in-situ soil fabric and may generate locked-in pseudo-stresses (Fu et al., 2023; Mujah et al., 2016).

The long-term stability of soils treated with calcite is largely dependent on the groundwater environmental conditions. Under favorable conditions, the expected service life can considerably exceed the standard engineering requirements, typically in the range of 30–50 years. Nonetheless, under adverse conditions the enhancements may degrade more rapidly than the structures they aim to support (DeJong and Kavazanjian, 2019).

Numerous laboratory and field-scale studies have demonstrated the effectiveness of MICP in improving the strength, stiffness, and permeability characteristics of sands (DeJong et al., 2006; Feng and Montoya, 2015; Montoya and DeJong, 2015; Gomez et al., 2016; Babaeizad et al., 2025). However, treatment efficiency is also highly dependent on the initial soil properties. Natural soils differ in grain size, gradation, and grain shape, each of which can alter permeability, transport of the introduced solutions, and the final spatial distribution of calcite (Nafisi et al., 2020, Fu et al., 2023). For future field applications, it is therefore crucial to identify the soil intrinsic characteristics affecting MICP outcomes most significantly, which enables more predictable and reliable treatment designs. However, systematic studies that isolate these effects are still limited.

The first part of this study investigates the effect of mean grain size in element-scale experiments, while maintaining other soil properties and treatment conditions constant. Three sands with different mean grain sizes but similar coefficients of uniformity were treated under identical conditions. Their pre- and post-treatment response was examined through drained monotonic triaxial tests and spatial calcite content measurements. In the second part, a model-scale experiment was conducted with one of the sands being treated in a model box with a model foundation placed on top of the soil surface. Here, three injection–extraction methods were applied, and the improvement was assessed by comparing the load–settlement responses along with calcite distribution within the sample.

2 MATERIALS USED

Three different sands were used for the element-scale tests to investigate the isolated effect of mean grain size on the mechanical behavior of sandy soils before and after biocementation. As shown in Figure 1 and Table 1, all materials were uniformly graded with identical coefficients of uniformity, while their mean grain sizes were varied to allow its effect on strength and stiffness after treatment to be evaluated directly. The soils are referred to as KFS (Karlsruhe

fine sand), 0.1–0.5 (sand with grain sizes between 0.1–0.5 mm), and 0.5–1 (sand with grain sizes between 0.5–1 mm).

3 EXPERIMENTAL METHODS

3.1 Triaxial tests

To evaluate the impact of biocementation on soil mechanical behavior, two types of cylindrical samples (50 mm diameter, 100 mm height) were prepared: uncemented reference and biocemented samples.

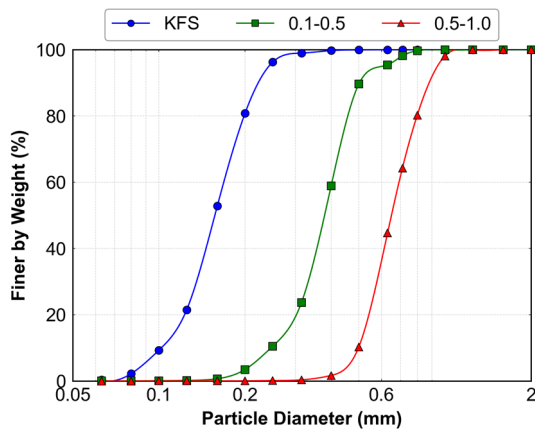


Figure 1. Grain size distribution curves of the used sands.

Table 1. Material parameters of the used sands.

Soil	D_{50} (mm)	C_u	ρ_s (g/cm ³)	e_{max}	e_{min}
KFS	0.16	1.68	2.65	1.054	0.658
0.1-0.5	0.38	1.60	2.63	0.97	0.56
0.5-1.0	0.65	1.43	2.65	0.859	0.53

Uncemented samples were prepared directly in the triaxial cell, by placing the sands into the split mold in five layers at a water content of 5% and a target relative density of 30%. Biocemented samples, in contrast were prepared in external split molds lined with membranes and maintained under vacuum during treatment to ensure sample stability and minimize disturbance.

The ureolytic bacterium *Sporosarcina pasteurii* purchased from the German microorganisms collection (DSMZ) was used as the biocementation catalyzer. It was cultivated in sterilized nutrient medium (components in Table 2) and incubated on a shaker at 180 rpm until an optical density (OD) of 0.8–1.2 was achieved. The prepared bacterial suspension was afterwards injected at 1.2 pore volumes (PV), followed by a 6-hour retention period to allow for a better attachment of the bacterial cells to the sand grains. Subsequently, the cementation solution, mainly consisting of urea and calcium chloride was supplied in 10 injection cycles. After the final treatment cycle, samples were rinsed with five PV of deionized water to remove unreacted constituents.

Afterwards, the molds were dismantled and the samples were cautiously transferred to the triaxial cell for further testing. All triaxial tests were conducted under an effective confining stress of 100 kPa and drained loading conditions after an isotropic consolidation.

3.1.1 Calcite content determination

After the triaxial tests, subsamples were extracted from the top, middle, and bottom of each sample to evaluate calcite content along samples' height and the relationship between the

cementation level and shear strength. The calcite content determination was performed based on the German standard code DIN 18129, which is based on the .

Table 2. Components of the bacteria solution

Constituent	Concentration
Tryptone	15 g/L
Soybean peptone	5 g/L
Sodium chloride	5 g/L
Urea	20 g/L
<i>Sporosarcina pasteurii</i>	1-1.2 (OD)

3.2 Model box tests

To evaluate the effectiveness of biocementation at a larger scale, a series of model box experiments was carried out using Karlsruhe fine sand (KFS). The sand was placed in a rectangular model box with internal dimensions of 56×36×30 cm. A model foundation (4×4×1.5 cm) was positioned on the soil surface to assess the changes in the load-settlement behavior before and after the soil biocementation. Fig. 2 (a-b) shows the layout of the treatment box, including the arrangement of the injection and extraction tubes, as well as the position of the model foundation on the soil surface.

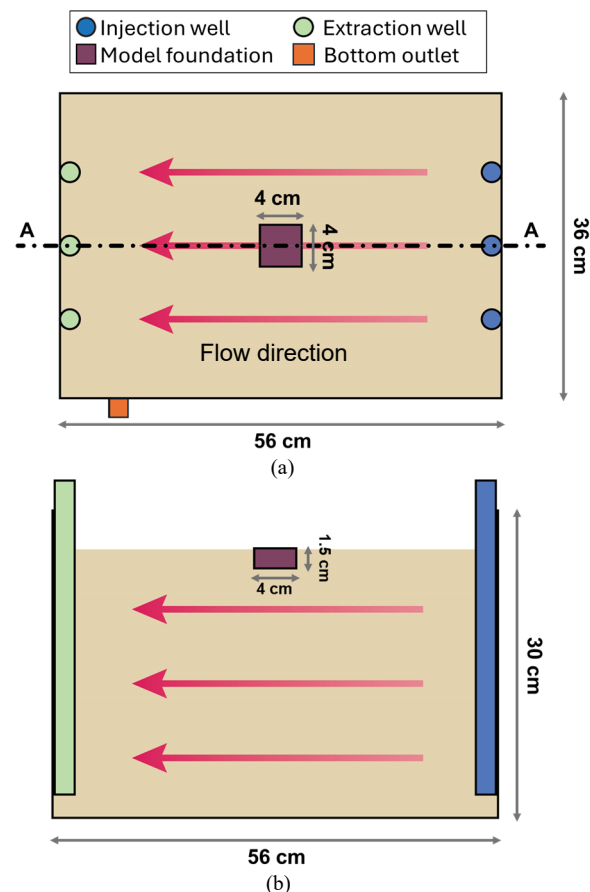


Figure 2. (a) Plan view, and (b) cross section (A-A) of the treatment box

The bacteria and cementation solution used for the soil biocementation in the box were prepared with the same procedures as in the element-scale tests but at a larger volume. Moreover, to reduce treatment time a higher concentration was

considered for the cementation solution components. At the beginning of the treatment sequence, 1.2 PV of bacterial suspension was injected through the three injection tubes installed on the right side of the box, while being extracted from the left side using a vacuum pump. After the retention period, the cementation solution was injected and extracted with the same flow configuration as the bacteria solution. The cementation solution was overall injected in three injection cycles. Depending on the test design, the solution extraction was either done from a single outlet located at the bottom of the box (Fig. 2(a)) or through three extraction tubes installed on the left side of the box (Fig. 2(a-b)).

A total of three model box experiments were performed, each applying the same injection sequence but different drainage conditions, as indicated in Table 3. These variations were designed to evaluate how drainage control influences calcite precipitation efficiency and uniformity. In the first test, drainage was conducted in parallel with injection, allowing the solution to exit through the outlet at the bottom of the box. In the second test, the outlet at the bottom was closed and the solution was extracted through the three extraction points on the left side. In that test series, the solution extraction was regulated to maintain the level of the solution 1 to 2 cm above the surface of the sample. The solution was drained only shortly before the next injection to prolong contact time between the soil surface and the solution. In the third test, drainage again occurred in parallel with injection using the three extraction pipes on the left side. However, in contrast to the second test no excess solution was maintained on the soil surface between injections. Load–settlement behavior was obtained for both uncemented and biocemented samples using a load press and a displacement transducer (Fig. 3 (a-b)). The improvement in foundation response was evaluated by comparing the load–settlement behavior before and after treatment.

Table 3. Overview of the variations in the biocementation experiments

Experiment	Drainage system
MICP1	Injected-Extracted from a single valve at the bottom
MICP2	Injected-Extracted through pipes
MICP3	Injected-Retained-Extracted through pipes

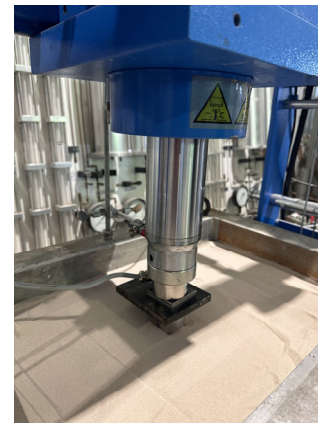
After the last treatment cycle, the sample was rinsed with tap water to remove unreacted components. Following the loading test, subsamples of 8–10 g were taken from different locations within the treated soil to determine calcite content distribution.

4 Results and discussion

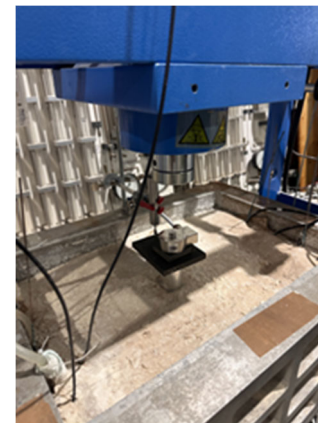
4.1 Triaxial tests

The results of the drained monotonic triaxial tests are shown in terms of deviatoric stress and volumetric strain versus axial strain in Fig. 4a and 4b, respectively. As shown in Fig. 4a, peak deviatoric stresses increased substantially after treatment, with the magnitude of improvement closely linked to mean grain size. The finest material (KFS) achieved the highest calcite content (CC) of 5.49% and reached peak deviatoric stress of around 585 kPa, whereas the coarsest sand (0.5–1 mm) exhibited a modest strength gain at a calcite content of 2.67%. The 0.1–0.5 sand showed an identical response to that of KFS, but at a lower calcite content (3.65%). These results indicate that finer-grained sands promote more efficient calcite bonding due to their larger number of interparticle contacts and smaller

pore spaces, while in coarser sands a substantial portion of the injected solutions drains rapidly from the sample, leading to reduced precipitation and weaker interparticle bonding at the same number of treatment cycles. Similar trends have been reported by Nafisi et al. (2020).



(a)



(b)

Figure 3. Determination of the load-settlement response for the model foundation on (a) uncemented, and (b) cemented sand.

Quantitative comparisons of stiffness and strength parameters further highlight these trends. As shown in Table 4, for KFS, the secant modulus (E_{50}) increased from 16.12 MPa in the uncemented state to 88.3 MPa after treatment. The 0.1–0.5 mm sand also showed a substantial increase, with E_{50} rising from 12.4 MPa to 244.8 MPa. In contrast, the 0.5–1 mm sand exhibited a smaller improvement, with E_{50} increasing from 40.2 MPa to 135.9 MPa. These values confirm that stiffness enhancement through biocementation is more pronounced in finer sands.

Substantial increases in peak friction angle (ϕ'_{peak}) were also observed across all treated soils. As all triaxial tests were conducted under a single confining pressure of 100 kPa, ϕ'_{peak} was evaluated under the assumption of zero cohesion, yielding an upper-bound estimate of frictional strength - an approach that has also been reported as one of the methods employed by Feng and Montoya (2016). Based on that assumption, KFS showed an increase from 31.6° to 48.2°, while 0.1–0.5 mm sand increased from 32° to 49°, and 0.5–1 mm sand from 32.9° to 44.4°. The increases in the peak friction angle can be related to the primary interparticle bonding and particle roughness induced by calcite precipitates (Feng and Montoya (2016); DeJong et al. (2022)). Overall, both the stress–strain curves (Figure 4a) and the stiffness/strength parameters (Table 4) demonstrate that MICP is most effective in finer uniformly graded sands under identical treatment conditions.

In terms of volumetric behavior, the response of uncemented sands exhibited dependence on grain size at the same relative densities. As shown in Fig. 4b, the two finer sands (KFS and 0.1-0.5) showed consistent contraction throughout shearing. In contrast, the coarser sand (0.5-1) showed a clearer tendency toward dilation with the shearing progress. After biocementation, all three sands developed noticeably more dilation than in their untreated state. In all biocemented samples, dilation was initially suppressed, as the calcite bonds should first mobilize and resist deformation. Once yielding occurs and these bonds begin to break, the soil shows increasing dilation, with the level of dilation becoming greater as the strain progresses (Wang et al. (2021)). Thus, this micromechanical process changed the behavior of finer sands from contractive to dilative and intensified the natural dilation of the coarser sand.

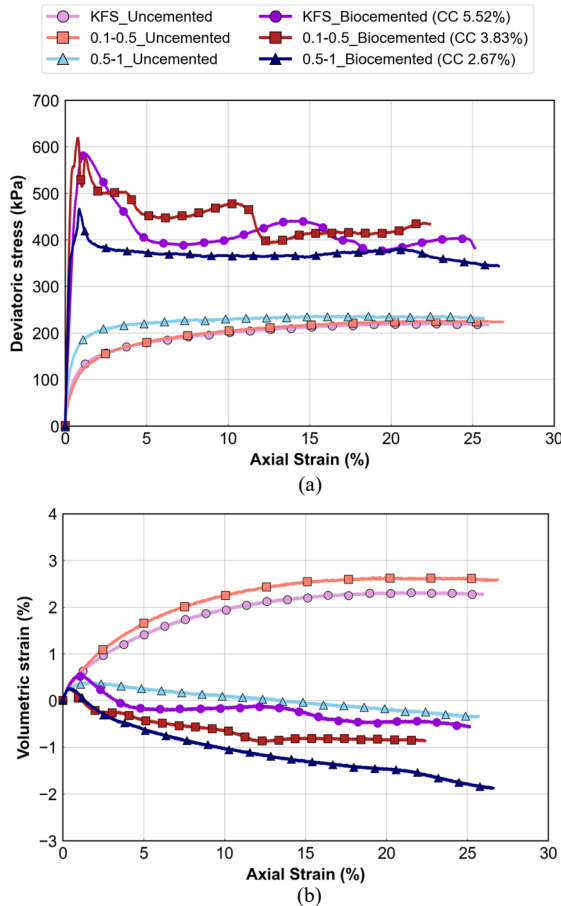


Figure 4. (a) Deviatoric stress vs. strain curves of uncemented and biocemented soil samples, (b) Volumetric vs. axial strain curves of uncemented and biocemented soil samples

Table 4. Shear strength parameters of the uncemented and cemented sands

Sand	CC (%)	q_{max} (kPa)	E_{50} (MPa)	ϕ'_{peak} (°)
KFS_Uncemented	0	220	16.1	31.6
KFS_Biocemented	5.49	585.1	88.3	48.2
0.1-0.5_Uncemented	0	225.9	12.4	32
0.1-0.5_Biocemented	3.83	615.8	244.8	49
0.5-1_Uncemented	0	237.7	40.2	32.9
0.5-1_Biocemented	2.67	466.6	135.9	44.4

4.2 Model box tests

The load-settlement curves of the biocemented samples (MICP1-3) and their associated calcite content distributions

indicate that even relatively low calcite contents can contribute to an improvement in the bearing capacity of the soil (Fig. 5 and 6).

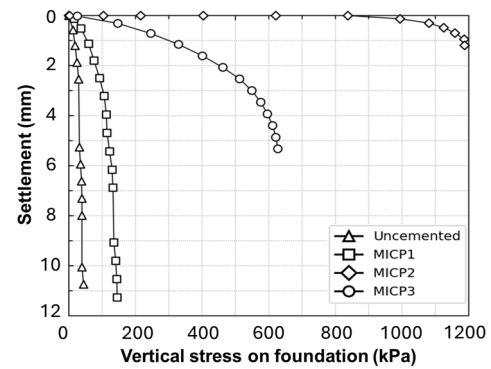


Figure 5. Load-settlement curves of uncemented and cemented soils (tests MICP1, MICP2, MICP3)

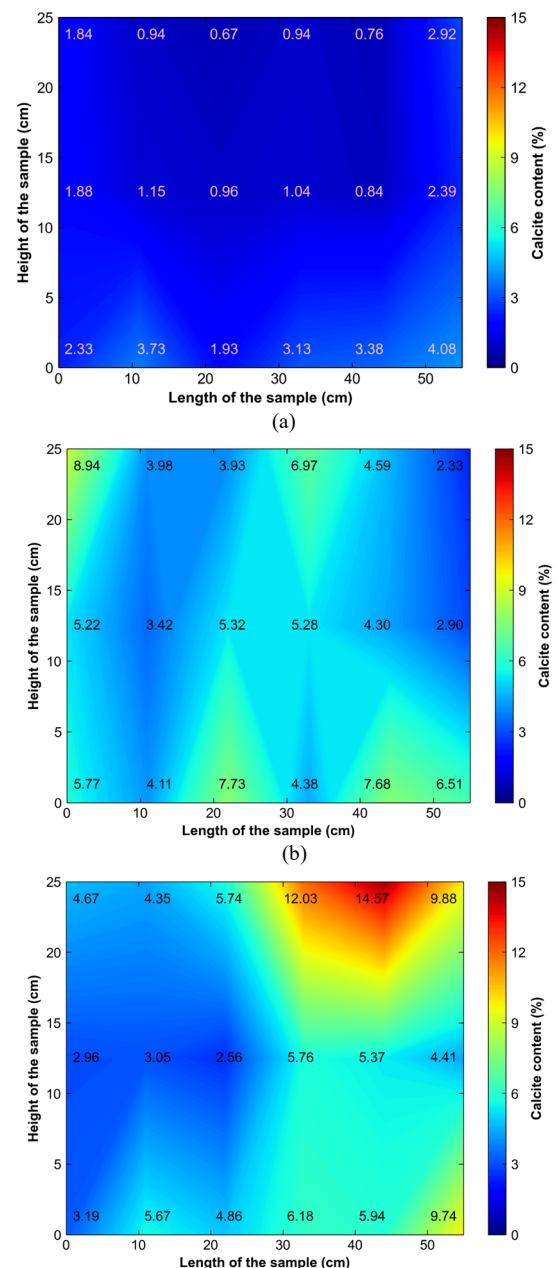


Figure 6. Calcite content measured at sampling points on the middle cross section following (a) MICP1, (b) MICP2, and (c) MICP3.

The MICP1 sample, with the lowest calcite content of up to 1% below the foundation (Fig. 5 and 6a) exhibited a moderate improvement in bearing capacity compared to the untreated sample. Its load-settlement curve showed delayed settlement initiation and slightly higher maximum stress, reflecting the stabilizing effect of limited calcite bonding. However, drainage clogging occurred during the second treatment cycle, preventing further treatment and resulting in a lower degree of cementation than in the other tests, which restricted its overall effectiveness. The MICP2 sample, with calcite content of up to 8.5% below the foundation (Fig. 5 and 6b), showed a more significant improvement than MICP1. In that case, settlement remained minimal up to stresses of about 400 kPa, reflecting the stronger bonding achieved between soil grains. The MICP3 sample with the highest calcite content of up to 12% below the foundation yielded the most significant increase in bearing capacity (Fig. 5 and 6c). Here, no settlement is virtually visible up to a stress of approximately 800 kPa and only begins at very high stresses. However, due to the strongly localized precipitation, MICP3 also exhibited pronounced uneven settlement, highlighting the importance of achieving more uniform calcite distribution. This demonstrates that although a higher degree of precipitation can significantly increase both bearing capacity and stiffness a more reliable and consistent performance may be achieved if the spatial homogeneity of calcite precipitation is further improved for future large-scale applications.

5 CONCLUDING REMARKS

This study investigated the influence of mean grain size on biocementation at element scale and evaluated the effect of different injection–drainage strategies in model box tests on the spatial calcite distribution and the load-settlement curves of model foundations. The results demonstrated that, under identical treatment conditions, uniformly graded sands with finer grain sizes yielded higher average calcite contents due to a greater number of interparticle contacts. This, in turn, led to higher shear strength parameters, with the most favorable response observed for sands with mean grain sizes in the range of approximately 0.16–0.38 mm.

The model box experiments further confirmed that biocementation can enhance the bearing capacity of sandy soils even at relatively low cementation levels. However, the resistance to settlement was directly linked to the final calcite content, with higher contents yielding more substantial improvements. A longer contact time of the cementation solution increased calcite contents near the top but reduced overall uniformity. These findings emphasize that, for practical design, not only the overall amount of precipitation but also its spatial distribution must be carefully controlled. Improvements such as regulating flow rates or employing injections from multiple sides may help achieve more uniform calcite distributions, thereby reducing differential settlement and ensuring more reliable foundation performance.

Moreover, although the results of this and many previous studies prove the efficiency of the MICP method in enhancing the mechanical properties of granular soils, further open questions should be clarified before the commercialization of this treatment method. One of the most important remaining challenges is the management of the ammonium byproducts from the urea hydrolysis process. Although different strategies have been proposed in previous studies to either collect the produced ammonium or rinse it with cation rich solutions, the approaches cannot be considered as cost friendly for the industrial use of the treatment method. Thus, development of

more cost-effective posttreatment soil remediation is crucial for future studies.

6 ACKNOWLEDGEMENTS

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