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Shear wave velocity and permeability evolution of MICP-treated carbonate bearing sand

Vitesse des ondes de cisaillement et évolution de la perméabilité des sables carbonatés traités au MICP

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ABSTRACT: Microbially induced calcite precipitation (MICP), a promising method developed for soil stabilization, demonstrates potential as an eco-friendly approach capable of significantly improving the geotechnical properties of soil. However, research indicating the evolution of permeability requires further investigation to substantiate the effectiveness of MICP treatment in enhancing permeability. In this aspect, this study investigates the evolution of shear wave velocity (V_s) and permeability (k) in MICP-treated carbonate bearing sands. Compacted specimens were subjected to MICP-treatment using 5ml/min and 10ml/min injection flow velocities. Injection velocities of 5ml/min produced heterogeneous $CaCO_3$ precipitation across the sample, with maximum precipitation near the injection point after 6 cementation cycles. This led to clogging near the injection point, resulting in a decrease in k by an order of magnitude and a constant V_s, showing a maximum value of 554.2m/s. On the other hand, specimen subjected to a 10ml/min injection velocity showed a relative homogeneous $CaCO_3$ distribution throughout. This resulted in a consistent permeability and V_s continued to increase beyond 6 cementation cycles and reached a constant value of 950m/s after 13 cementation cycles. Thus, injection flow velocity is an important variable to be considered when investigating permeability modifications in MICP treated soils.

RÉSUMÉ: La précipitation de calcite induite par voie microbienne (MICP), une méthode prometteuse développée pour la stabilisation des sols, démontre son potentiel en tant qu'approche respectueuse de l'environnement capable d'améliorer de manière significative les propriétés géotechniques des sols. Cependant, la recherche indiquant l'évolution de la perméabilité nécessite une étude plus approfondie pour prouver l'efficacité du traitement MICP dans l'amélioration de la perméabilité. Dans cette optique, cette étude examine l'évolution de la vitesse des ondes de cisaillement (V_s) et de la perméabilité (k) dans des sables carbonatés traités au MICP. Des échantillons compactés ont été soumis à un traitement MICP en utilisant des vitesses d'injection de 5ml/min et 10ml/min. Des vitesses d'injection de 5ml/min ont produit une précipitation hétérogène de $CaCO_3$ dans l'échantillon, avec une précipitation maximale près du point d'injection après 6 cycles de cimentation. Cela a conduit à un colmatage près du point d'injection, entraînant une diminution de k d'un ordre de grandeur et une V_s constante, montrant une valeur maximale de 554,2m/s. D'autre part, l'échantillon soumis à une vitesse d'injection de 10ml/min a montré une distribution relativement homogène du $CaCO_3$ dans l'ensemble de l'échantillon. Cela a entraîné une perméabilité constante et V_s a continué à augmenter au-delà de 6 cycles de cimentation et a atteint une valeur constante de 950m/s après 13 cycles de cimentation. Ainsi, la vitesse d'injection est une variable importante à prendre en compte lors de l'étude des modifications de perméabilité dans les sols traités au MICP.

Keywords: MICP-treated sand; flow velocity; shear wave velocity; permeability; calcium carbonate precipitation.

1 INTRODUCTION

MICP is a biocementation method in which microbial activity drives the precipitation of calcium carbonate at within and/or around soil particle to improve engineering properties (Fu et al., 2023; Tang et al., 2020).

Several laboratory studies have shown the efficacy of MICP treatment in improving the strength, stiffness, and bearing capacity of soils (Lui et al., 2021; Fu et al, 2023). However, studies investigating the impact of MICP-treatment on the soil permeability have demonstrated a range of effects (Jian and Soga, 2017; Martinez et al., 2013; Sharma et al., 2021; Whiffin et al., 2007). For example, Sharma et al. (2021) documented the permeability evolution in MICP treated sands after 6, 12, and 18 days of treatment. They reported a maximum decrease of 91% in the coefficient of permeability (k) after 18 days in MICP-treated sand compared with an untreated specimen. This reduction in 'k' was attributed to the decrease in porosity resulting from calcium-carbonate ($CaCO_3$) precipitation. Similarly, Martinez et al. (2013) reported a decrease in 'k' of up to two orders in magnitude with an increase in shear wave velocity (V_s) of about 1000 m/s in MICP treated Ottawa 50-70 sands. On the other hand, Whiffin et al. (2007) reported that the 'k' value of MICP-treated sand remained almost unchanged, though a significant development in the soil's strength and stiffness occurred. Likewise, Jiang and Soga (2017) reported a limited impact of cementation on the reduction of 'k' in MICP-treated sand-gravel mixture. The impact of MICP-treatment on 'k' has been attributed to several factors. Zamani and Montoya (2016) showed that the reduction in 'k' with increase in cementation level is governed by soil grain size. Other studies reported that the concentration of cementation solutions has a significant impact on the reduction of 'k' (Harkes et al., 2010; Tang et al., 2020). These uncertainties motivated the present study to investigate further the impact of selected MICP-treatment parameters on the permeability evolution of sands.

This study aims to investigate the 'V_s' and 'k' evolution in MICP-treated carbonate-bearing sands subjected to different flow rates of solution injections. The first part of the study presents the 'V_s' and 'k' monitored throughout the MICP-treatment process and in the second part, the variability in $CaCO_3$ precipitation throughout the specimens were measured to provide an interpretative framework for the observed results.

2 MATERIALS AND METHODOLOGY

2.1 Soil and solutions properties

Fine sand, sampled from Blessington quarry, Ireland, with a fine content (< 0.063mm) of 35% and initial carbonate content of 20% was used. Four types of chemical solutions were prepared. To mimic the field's groundwater, artificial groundwater (AGW) was prepared for preparation and saturation of the specimens. Yeast (Y), Biostimulation (BS), and Cementation (CM) solutions were prepared for the MICP-treatment. Further details of these solutions are presented in Table 1.

2.2 Sample preparation

Air-dried sands were placed in soil columns of 5cm diameter, and 10cm height. The placement was made in three layers, with each layer tamped 15 times to reach the minimum void ratio of 0.53. Specimens were then fully saturated by pumping 1 pore volume flow (PVF) of AGW into the specimen from beneath.

Table 1. Chemical solutions.

Solutions	Composition and concentrations
AGW	Potassium Nitrate: 0.04mM; Magnesium sulphate: 0.45 mM; Calcium chloride: 1.75 mM; Sodium Nitrate: 0.04 mM; Sodium Bicarbonate: 1.10mM; Potassium Bicarbonate: 0.06mM
Y	Yeast extract: 0.2g/L; Sodium acetate trihydrate: 42.5mM
BS	Yeast extract: 0.2g/L; Sodium acetate trihydrate: 42.5mM; Urea: 350mM; Ammonium chloride: 100mM
CM	Yeast extract: 0.2g/L; Sodium acetate trihydrate: 42.5mM; Urea: 350mM; Ammonium chloride: 12.5mM; Calcium chloride: 250mM

2.3 MICP-treatment and shear wave velocity measurement

Saturated specimens were subjected to MICP treatment through biostimulation. This initially involves the injection of Y solution to enhance the growth of native ureolytic bacteria present in the soil. Then, 4 cycles of BS solutions (BS1-BS4) were injected to allow the bacteria to induce ureolytic reactions, thus producing carbonates. This was then followed by cementation cycles using cementation solutions to allow the precipitation of $CaCO_3$ (Tang et al., 2020). Throughout the cementation cycles, V_s was measured to monitor the stiffness evolution of the soil using bender elements, as per ASTM D8295-19 (2019). The cementation cycles continued until a constant V_s was reached to ensure that no further precipitation of $CaCO_3$ were possible.

2.4 Permeability measurement

All chemical solutions were injected through the inlet present at the base of the soil columns. Effluents were collected from the outlet located at the top of the column. The chemical solutions were injected at two different flow rates, i.e., at 5ml/min and 10ml/min using a pump. A constant hydraulic gradient is maintained throughout the injection between the pump and the injection point. The coefficient of permeability is calculated using Darcy's equation. In the following sections, specimens subjected to MICP treatment processes involving injection of solutions at 5ml/min and 10ml/min are represented as SP1, and SP2, respectively. Thus, SP1 is the specimens subjected to relatively slower MICP treatment than SP2.

2.5 Calcium-carbonate measurement

At the end of cementation cycles for SP1 and SP2, specimens were sampled from top, middle, and bottom parts of the samples to check the spatial distribution of calcite precipitation. Calcite was measured as per ASTM D4373-02 (2017).

3 RESULTS AND DISCUSSIONS

Figure 1 presents the V_s evolution throughout the cementation cycles in specimens SP1 and SP2. SP1 reached a V_s of 554.2m/s after the 6 cementation cycles. With further injection of cementation solutions, V_s showed no change. This indicates that no further $CaCO_3$ precipitations can occur, as the increase in V_s is reported to be directly related to the $CaCO_3$ precipitations (Lui et al., 2021). Thus, the injection was stopped after the 8th cementation cycle. By contrast, the V_s value obtained after 6 cementation cycles in SP2 was slightly lower and reached the same value as SP1 after the 8 cementation cycles. This V_s increased further with further injection of cementation solutions and reached about 950m/s after 13 cementation cycles. This value remained constant with further injection of cementation solutions up to 15 cementation cycles.

Figure 2 presents the permeability evolution in specimens SP1 and SP2. The initial value of ‘k’ in specimen SP1 is lower than specimen SP2. This is attributed to the difference in flow velocity maintained in specimens SP1 and SP2, since the rate of discharge of solution is directly proportional to ‘k’ at a given hydraulic gradient as per Darcy’s law. Further, with incremental cementation cycles in SP1, the magnitude of ‘k’ reduced by an order of magnitude, which corresponds to the constant value of V_s reached after 6 to 8 cementation cycle (Figure 1). However, for specimen SP2, where the cementation cycles continued up to 15 cementation cycles, the magnitude of ‘k’ remained in between 6.8×10^{-6} to 5.7×10^{-6} m/s, thus, showing no significant change.

Table 2 presents the percentage increment in $CaCO_3$ measured in the specimens sampled from the three layers of SP1 and SP2, at the end of 8 and 15 cementation cycles, respectively. The percentage increment is represented with respect to the untreated sand. At the end of cementation cycle, the weight % $CaCO_3$ was 6% higher in the bottom sampled specimen of SP1, near the injection point compared to the top and middle sampled specimens. Such heterogeneity in $CaCO_3$ distribution has been a concern in several MICP studies (Fu et al., 2023; Tang et al., 2020). However, in specimen SP2, the distribution of $CaCO_3$ is relatively homogeneous irrespective of position in the column (Table 2). Such differences in $CaCO_3$ distribution between specimens SP1 and SP2 highlight the fact that the low flow velocity (5ml/min) in SP1 caused maximum deposition of $CaCO_3$ near to the injection point. This caused clogging, which was confirmed after observing white thick precipitation between the porous stone and the specimen near the injection point. This probably restricted the flow of calcium ions to the middle and top region of SP1 beyond 6 cementation cycle. This phenomenon results in a decrease of permeability (Figure 2) and restricted further increase in V_s with further injection of cementation solutions (Figure 1).

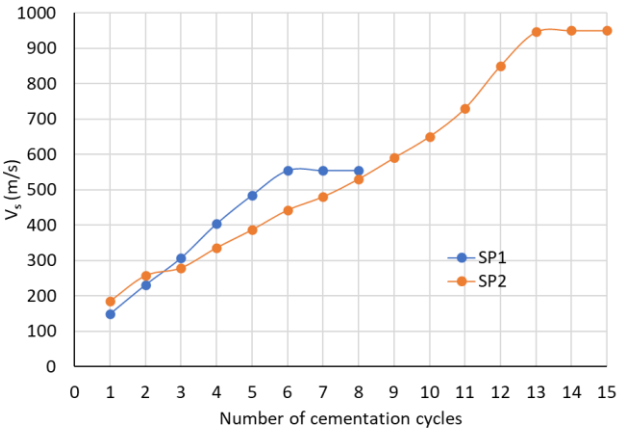

Figure 1. Shear wave velocity evolution in SP1 and SP2.

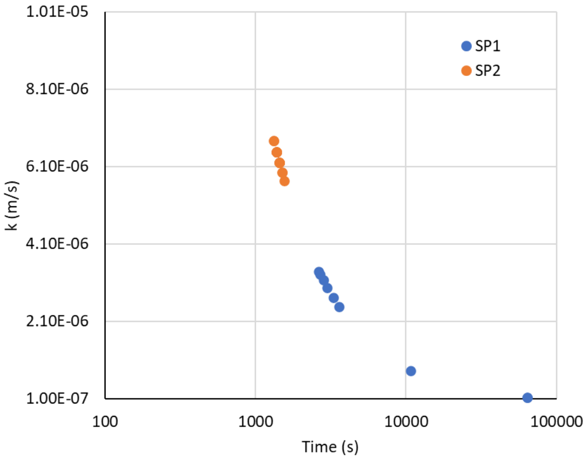

Figure 2. Permeability measured in SP1 and SP2.

A higher flow velocity of 10ml/min in SP2 enabled uniform calcium dispersal throughout the sample uniformly beyond the 6th cementation cycles, resulting in a more homogeneous $CaCO_3$ distribution (Table 2). This phenomenon increases the V_s beyond the 6th cementation cycles (Figure 1). A homogeneity in $CaCO_3$ distribution prevented clogging near the injection point. This led to no significant change in the permeability (Figure 2), unlike SP1.

Table 2. $CaCO_3$ percentage in SP1 and SP2.

Specimens	$CaCO_3$ (%)		
	Top	**Middel**	**Bottom**
SP1	10	10	16
SP2	12	12	13

4 CONCLUSIONS

The study investigated the shear wave velocity and permeability evolution in a MICP-treated carbonate bearing sand column subjected to different flow velocities. The main conclusions are:

1) A greater flow velocity (10ml/min) produced a more homogeneous $CaCO_3$ distribution throughout the MICP-treated specimen. compared with that subjected to 5ml/min flow velocity.
2) Deposition of $CaCO_3$ near the injection point in specimen subjected to low flow velocity MICP treatments, led to clogging of specimens. This restricted the uniform flow of calcium ions throughout the specimen, thus, restricting further increase in shear wave velocity. For the same type of compacted specimens, specimen subjected to 10ml/min flow velocity showed a increase in shear wave velocity up to 13 cementation cycles, while that subjected to a 5ml/min flow velocity did not show an increase in shear wave velocity after the 6th cementation cycles.
3) Clogging of the specimen near the injection point led to a decrease in permeability. The k value decreased by an order of magnitude in the specimen subjected to flow velocity of 5ml/min, whereas it remain unchanged in the corresponding specimen subjected to a flow rate of 10ml/min.

This study highlights that flow velocity is an important parameter that needs to be considered which investigating the stiffness and permeability evolution in MICP treated sand columns.

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