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The comparison of the performance of biological improvement in sandy soils by the injection and the flow-through methods

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Abstract

Bio-improvement has been identified as an environmentally friendly method, Microbially Induced Calcium Carbonate Precipitation (MICP) is the predominant technique in this domain. The four main methods introduced for MICP are the injection, surface injection or flow-through, immersion, and mixed methods. Among these, the injection and the flow-through methods hold particular significance. In this study, the efficiency and performance of these two methods were investigated in soils with different relative densities and varying volumes of bacterial suspension injection. To assess the efficacy of these methods, various tests including optical density, Urease activity, permeability, uniaxial strength, calcium carbonate precipitation percentage were conducted. The flow-through method, with its easier implementation, absence of the need for special equipment, minimal reduction in permeability, more uniform dispersion of the resulting cement, and the ability to achieve comparable strength to the injection method when using an injection volume equal to the pore volume in high relative density, stands out as the more suitable and economical approach for improving sandy soils. Despite its cost-effective implementation, the flow-through method necessitates more injection cycles, particularly in the injection volume of two-thirds and one-third of the pore volume, to achieve the same strength as the injection method. This aspect diminishes the economic difference between improvement using the injection method and the flow-through method in laboratory. This aspect diminishes the economic difference between improvement using the injection method and the flow-through method in a laboratory conditions.

Keywords: *Microbial induced calcite precipitation, Injection, Surface injection with Flow-through, Relative density, Bio-improvement.*

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Extended Abstract:

1. Introduction

Bio-cement improvement methods are categorized into four main groups: injection, flow-through (surface percolation) method, immersion, and mixing methods (Xu et al. 2021). Among these methods, the injection is the most popular one. In this technique, the cementation solution and the bacterial suspension are injected horizontally or vertically using a peristaltic pump. The flow-through method (FTM) relies on gravity, and no external pressure is involved and cement solution and bacterial suspension are poured and freely percolated into the sample (Jiang and Soga 2017; Gu et al. 2018; Karimian et al. 2020).

In Karimian et al. (2020) 's research, the drain valve is kept closed during each transfer of bacterial suspension or cementation solution to the sample. This deviates from typical conditions and introduces a departure from gravity-driven improvement processes. Moreover, in the study conducted by Mwandira et al. (2019), a combined approach is employed wherein the cementation solution is transferred using the flow-through. However, during the transfer of bacterial suspension, the injection method is utilized. Consequently, natural gravity flow conditions are not consistently established throughout all stages of the process. Ultimately, this method is compared with the immersion method. In the True FTM, it is essential to ensure that the liquids exit path remains fully open throughout the remediation process. This ensures that the bacteria suspension and cementation solution can efficiently permeate the sample under the influence of gravity and exit freely. The execution of the mentioned case and the comparison with the important and practical method of injection have been infrequently observed in previous studies.

Acknowledging that the injection method and the FTM are two crucial and widely employed techniques in bio-cement improvement. Hence, there is limited research available to comprehensively investigate and compare these two methods concurrently, taking into account other factors like soil density and varying volumes of bacterial suspension. In the present study, the appropriate and effective FTM was employed throughout the entire improvement process, while the injection method served as a basis for comparison. Additionally, considering the natural occurrence of sandy soils with varying densities, this aspect was taken into account in the experimental design. In this study, beyond the comparative analysis of the two mentioned improvement methods, an exploration into the impact of employing various volumes of bacterial suspensions at varying relative densities has been conducted. Through tests encompassing optical density, Urease activity, permeability, unconfined compressive strength, and the determination of calcium carbonate precipitation, the study delves into both injection method and FTM. The investigation focuses on their effects on permeability, strength, and the percentage of calcium carbonate precipitation.

2. Materials and methods

A poorly graded silica sand was used in all soil experiments. According to the unified soil classification system (USCS), this soil is classified as SP. Numerous earlier investigations have employed B. pasteurii from the Ureolytic family to augment the efficiency of the bio-mineralization process. Organisms were cultivated under aerobic batch conditions in a medium containing 10 g/L of ammonium chloride, 20 g/L of yeast extract, and 10 µmol/L of nickel chloride at a pH of 8.5 (Rowshanbakht et al. 2016; Whiffin et al. 2007; Harkes et al. 2010). $CaCO_3$ precipitation was induced by hydrolysis of Urea in a solution with calcium chloride (Nemati et al. 2005; DeJong et al. 2010; Whiffin et al. 2007). Many researchers have used cementation solution with equimolar Urea and Ca^{+2}

to conduct experiments (Zhao et al. 2014; Al Qabany et al. 2012). In this study, identical concentrations of Urea and 1 M calcium chloride were employed. A one molar Urea solution, sterilized through filtration, and a one molar calcium chloride solution, autoclaved, were utilized in this experiment. Therefore, dry sand with relative densities of 85%, 70%, and 40% was meticulously prepared inside two-piece cylindrical moulds (PVC), each with a diameter of 3.6 cm and a height of 22 cm. In the injection method, a 20 cm sand column is established within the pipe, blocked by 1 cm layers of gravel filter and washing pad (Scotch-Brite) both above and below the sample. In the FTM, a 15 cm sand column is created within the tube, accompanied by 1.5 cm layers of gravel filter and washing pa both above and below the sample. Additionally, a 4 cm empty space is maintained at the top of the tube to facilitate the unrestricted pouring of the bacterial suspension and cementing liquid. Following installation, the columns were saturated with autoclaved distilled water. In the injection method, solutions were introduced into the sand column using peristaltic pump pressure, while in the FTM, the solutions were poured into the vacant space above the sample, relying on gravity for the liquid flow. In three samples prepared with identical relative density, a bacterial suspension was introduced into the samples, corresponding to the volume of the pores, 2/3 of the volume of the pores, and 1/3 of the volume of the column pores, respectively. Initially, bacterial suspension with an optical density exceeding one was injected into the samples. Subsequently, a stabilization solution equal to the volume of the pores was promptly introduced into the columns. Then 4 times cementation solution enters the samples. To assess the efficacy of the injection, samples were obtained from the effluent liquid collected during the stabilization solution injection stage. Additionally, to monitor the performance and efficiency of the improvement method, optical density, Urease activity, permeability, uniaxial compressive strength and value of calcium carbonate precipitation were performed.

3. Tests results

It can be seen that in the improvement of injection and flow-through methods, by increasing the volume of injection, the efficiency of bacteria injection decreases in all densities, and with the increase of relative density, the efficiency of injection also increases to some extent.

In general, in the FTM, the injection efficiency is lower than the injection method. The optical density remaining in the columns in the injection method is higher than in the FTM, which indicates that more bacteria exit due to the open exit path in the FTM.

Observably, in both improvement methods and across all relative densities, the efficiency of injection diminishes as the increases of bacteria injection volume. Generally, the Urease activity within the columns of the FTM exhibits higher values compared to the injection method. Ultimately, in both methods, the lowest Urease activity is associated with the injection of one third of the volume of the pores, while the highest activity is linked to the injection of the full volume of the pores at a relative density of 85%. Permeability tests indicated that the injection method leads to a greater reduction in permeability values compared to the FTM. From each column, two samples were prepared for the uniaxial strength test. One sample was extracted from the upper half, located at the end of the sample in the injection method and near the injection point in the flow method. The second sample was taken from the lower half, situated near the injection point in the injection method and at the end of the sample in the flow method. In the injection method, contrary to the calcium carbonate percentage, the samples taken from the top of the column exhibit higher strength compared to those from the bottom of the column. However, in the FTM, both compressive strength and the percentage of calcite in the

lower part of the column surpass those in the upper part. Generally, the difference in strength between the upper and lower parts is less pronounced in the injection method compared to the FTM.
With an increase in the injection volume of bacterial suspension into the sample pores, the strength of samples decreases in the injection method and increases in the FTM. Notably, the strength of samples with a relative density of 70% and 40% in the FTM experiences a significant reduction compared to the injection method.

4. Conclusion

The injection and flow-through methods are two crucial and extensively employed approaches for enhancing Microbially Induced Calcium Carbonate Precipitation (MICP). This research delves into the investigation and analysis of both the injection method and the entirely gravity FTM applied to soils with varying densities and distinct volumes of bacterial suspension injection.
The assessment of injection efficiency, serving as a metric for gauging bacterial loss from the column, was conducted through the analysis of optical density and Urease activity. The findings reveal that, in both improvement methods, augmenting the volume of the injection bacterial suspension accompanied with a reduction in injection efficiency. Interestingly, alterations in relative density did not exhibit a significant impact on efficiency.
The average permeability reduction for the injection method is 75% of the initial permeability, while for the FTM, it is 25% of the permeability prior to the improvement. As the relative density increases, the uniaxial compressive strength demonstrates an elevation in both methods, despite a decrease in calcium carbonate content. Moreover, the magnitude of this strength increase is more pronounced in the FTM compared to the injection method. Notably, within the FTM, bottom part of samples exhibits significantly higher strength with the augmentation of bacterial suspension injection, attributed to a more uniform distribution of calcium carbonate in the lower regions, away from the injection point. The average percentage of calcium carbonate generated in the injection method surpasses that of the FTM. Across all relative densities and volume injection of bacterial suspension, the samples at the bottom of the column consistently exhibit higher calcium carbonate content than those at the top of the column. In SEM, XRD and XRF analyses, it was determined that the calcium carbonate precipitation corresponds to calcite, with a higher concentration of calcite observed in the lower section of the FTM compared to the upper part of the sample.
Regarding the injection method, using one-third of the injection pores of volume yielded more favorable results than larger injection volumes. However, the most optimal outcome was achieved in the FTM when employing an injection volume equal to the volume of the pores. Despite the FTM exhibiting reduced bacterial efficiency in low relative densities and demonstrating lower overall efficiency compared to the injection method, it remains a more suitable and economical approach for improving sandy soils in laboratory settings. This preference stems from the method's simplicity, absence of specialized equipment requirements, minimal reduction in permeability, more uniform dispersion of the precipitin cement, and its ability to provide equivalent strength as the injection method when using an injection volume equal to the pore volume in scenarios with high relative densities. However, achieving the same strength as the injection method in low relative density requires more injections in volumes corresponding to two-thirds and one-third of the pore volume.

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