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Calcium Carbonate Induced Precipitation for Soil Improvement by Urea Hydrolysing Bacteria

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ABSTRACT

Existing methods for improving the engineering properties of soils are diverse with respect to their final outcome. Grouting by chemical additives is currently one of the most commonly used soil stabilization techniques; however, it may have some environmental, reproducibility and health concerns. These drawbacks and the increasing population in regions of limited land drive the need to develop new technologies for ground improvement. The aim of this work is to introduce and examine a newly emerging microbiological process, known as microbial induced calcite precipitation (MICP), for soil stabilization. MICP is a promising technique that utilizes the metabolic pathway of bacteria to form calcite precipitation throughout the soil matrix, leading to an increase in soil strength and stiffness. The study investigates the geotechnical properties of bio-cemented silica sand under different degrees of saturation at which bio-cementation occurs. A series of laboratory experiments are conducted including the sieve analysis, permeability, unconfined compression strength and consolidated undrained tri-axial tests. The results confirm the potential of MICP as a viable alternative technique that can be used successfully for soil improvement in many geotechnical engineering applications, including liquefaction of sand deposits, slope stability and subgrade improvement. The results also indicate that higher soil strength can be obtained at lower degrees of saturation, negating the belief that bio-cemented soils need to be treated under full saturation conditions.

1. INTRODUCTION

More recent issues regarding the degradation of the environment has prompted

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developments in green technologies and sustainability. These issues are often motivated by the rapidly increasing global population and popularity of urban living, and engineers have been driven to alleviate many of these concerns. Engineering solutions are regularly impeded by geographical boundaries and inadequate soil conditions, which result in expensive designs and non-sustainable practices, including landfill and contamination of soils. Current soil improvement techniques include soil replacement, preloading to achieve consolidation, chemical admixture and grouting stabilization. These techniques are time consuming, expensive and in the case of grouting and admixture stabilization are environmentally detrimental. Therefore, continuing studies into finding alternative soil improvement methods are vital so that optimum performance, economic viability and environmental sustainability can be achieved.

Biologically induced precipitation of calcium carbonate or calcite (CaCO3) in soils is of particular interest to engineers and microbiologists. This method can alter the characteristics of soils in such a way that biologically induced soil modification can be used to increase the shear strength and stiffness of soil matrixes, while maintaining adequate permeability. An emerging technique based on the biological alteration of soil properties known as microbial induced calcite precipitation (MICP) has received recent attention as a viable soil stabilization alternative. This technique involves introducing aerobically cultivated bacteria with highly active urease enzymes into soil, harnessing the metabolic pathway to catalyze the hydrolysis of supplied urea into ammonium and carbonate. The chemical reaction of this process is as follows (Burbank et al. 2011):

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \tag{1}$$

In the presence of an introduced calcium source, often CaCl2, the calcite forms throughout the soil matrix based on the following chemical reaction (Stocks-Fischer et al. 1999):

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

The produced microbial-induced calcite bridges the adjacent soil particles by cementing the soil grains together to form cemented sand illustrative of calcareous rock (DeJong et al. 2006).

In this paper, the feasibility of MICP as a promising ground improvement technique is demonstrated via a series of laboratory tests using sand column experiments. The tests focus on the MICP application in a diverse range of in-situ degree of saturation conditions, to determine the highest optimal strength that can be accomplished. The paper also investigates the implications of MICP for potential industry acceptance as an environmentally friendly soil stabilization technique.

2. EXPERIMENTAL PROGRAM

2.1. Material Tested

The soil used in this study is poorly graded white silica sand that is classified by the Unified Soil Classification System (USCS) as SP. It has a coefficient of permeability of

4.0×10^{-4} m/s, indicating a good drainage material as proposed by Fell et al. (1992). The sand used has a maximum dry unit weight of 16 kN/m^3, no apparent cohesion and a friction angle of 25°. The particle size distribution curve of the sand used is shown in Fig. 1.

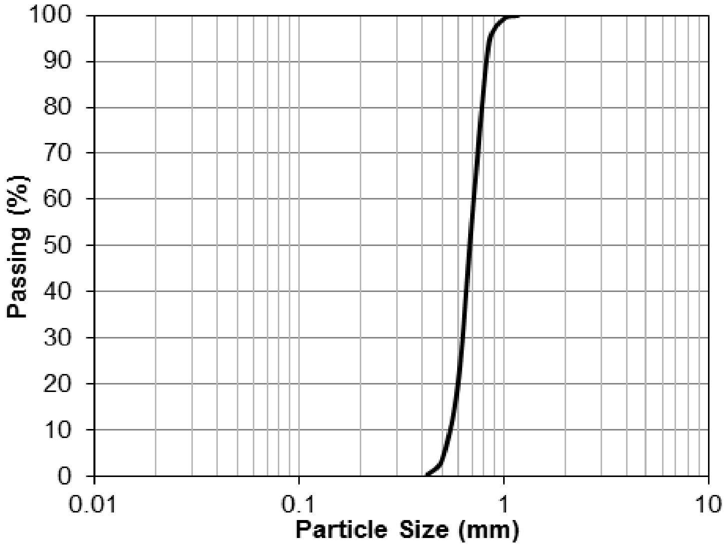


Fig. 1. Grain size distribution of the sand used.

2.2. Bio-cementation Treatment

Before carrying out the geotechnical engineering tests described later, three sand columns denoted as A, B and C were treated and prepared. Highly ureolytic bacteria were cultivated aerobically in the laboratory in four steps, commencing with the preparation of the supporting growth medium. The liquid medium was prepared using a ratio of 20 gm per litre of yeast extract added to deionised water. The following substances were added to the media: 0.17 M of Ammonium Sulphate, $[NH_4]_2SO_4$, and 0.1 mM of Nickel Chloride, $NiCl_2$. The pH adjustments were made using sodium hydroxide, NaOH, to obtain a basicity of 9.25. Before inoculation, the growth medium was sterilised by supplying an inoculum of approximately 2–5% pure bacteria culture into the medium to initiate microbial growth, then was incubated for an extended period of time. A maximum urease activity of about 0.6 mol-urea/litre/hr was obtained, indicating that the undiluted suspension of bacteria could produce calcium carbonate at a maximum rate of 0.3 mol/litre/hr (or 30 kg-$CaCO_3$/m^3/hr).

Reagent solutions containing $CaCl_2$ and urea, $CO(NH_2)_2$, were prepared and flushed through the sand column samples, as specified in Table 1. Throughout the flushing applications, specified degree of saturation was maintained using a pressurized vacuum to remove the previously supplied solution, leaving the next solution application as residual. The total amount of bio-cementation solution samples are given in Table 2.

Table 1. Bio-cementation solution required for flushing.

Process	Sand column		
	A	B	C
Approximate saturation (%)	30	65	100
Solution supplied (ml)	25	50	62.5
Bacteria supplied (ml)	25	50	62.5
Total (ml)	50	100	150

Table 2. Total flushes required to achieve various soil strength.

Supplied amount of reagent solution (ml)	Amount of flushes required		
	Sand column		
	A	B	C
250	5	3	2
500	10	5	4
750	15	8	5
1000	20	10	7

2.3. Permeability

Before Permeability is an important factor that governs the behaviour of fill under saturated conditions and often dictates the suitability of fill for specific applications. In this study, permeability testing was conducted to assess the impact of the MICP on the drainage ability of the bio-cemented soil samples. A series of constant head permeability tests was conducted on bio-cemented sand columns treated at different degrees of saturation. The tests were conducted in accordance with the Australian Standards AS 1289 (2007), and the results are shown in Fig. 2. It can be seen that there is a general trend of decreasing permeability with the increase of produced calcite content ($CaCO_3$) irrespective of the degree of saturation at which the soil was treated. It can also be seen that the permeability of almost all bio-cemented sand samples are greater than 1×10^{-6} m/s, indicative of good drainage materials. The ability of the treated soils to retain its permeability has a significant advantage in the sense that it allows additional applications of bio-cementation solution, permitting engineers to control the final design soil strength. Moreover, in contrary to most traditional methods of soil stabilisation, MICP will allow rapid dissipation of the excess pore water pressure upon loading, leading to instantaneous gaining of soil strength.

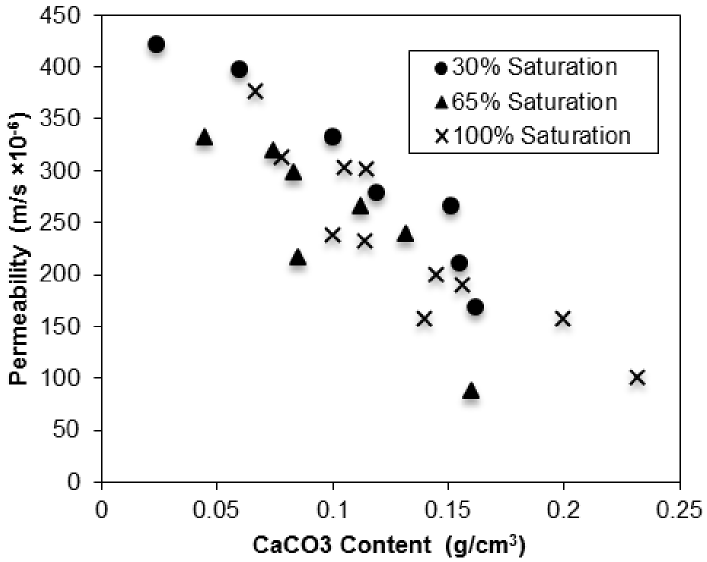


Fig. 2. Permeability of bio-cemented sand.

2.4. Undrianed Shear Strength

Due to the high permeability characteristics of granular materials such as sands, geotechnical engineers often work under drained conditions for most principal design situations. However, it is though important in areas predisposed to natural phenomena such as earthquakes that the design considerations under undrained conditions are governing. In this study, a series of unconfined compression tests are carried out to determine the improvement associated with the undrained shear strength response of bio-cemented samples, and the results are shown in Fig. 3. It can be seen that the increase in shear strength is directly proportional to the increase in the produced calcite content. It can also be identified that at the same calcite content, soil treated at lower degree of saturation exhibits significantly higher values of undrained shear strength. This can be attributed to the effectiveness of the calcite crystal formation within the soil matrix, which is clearly demonstrated by the images of the scanning electron microscopy shown in Fig. 4 for fully and partially saturated conditions.

For the fully saturated soil sample (Fig. 4a), the produced calcite is not fully formed at the inter-particle contact points of soil grains but floccules either on the grain surface or suspends in the pore space between the soil grains. These nucleation sites are ineffective and the formation of calcite provides no significant shear strength improvement. In the case of the partially saturated soil sample (Fig. 4b), the formation of calcite is observed to effectively coat over the soil particles and predominantly occurs at the effective areas of granular contact points. This calcite formation provides rationale to the significant reduction in CaCO3 content obtaining similar strengths of that witnessed at the saturated conditions. The above results indicate that the mechanical strength of micro-biological treated soils is mainly due to the effectiveness of calcite crystal formation rather than the total amount of produced calcite crystals. Given the verified effectiveness of the bio-cementation process in increasing the undrained shear strength of soil in a diverse range of in-situ conditions, MICP could be used as a viable solution to reduce the potential of granular soils to liquefy, providing the soil with greater resistance against the adverse deformation associated with the earthquakes induced loadings.

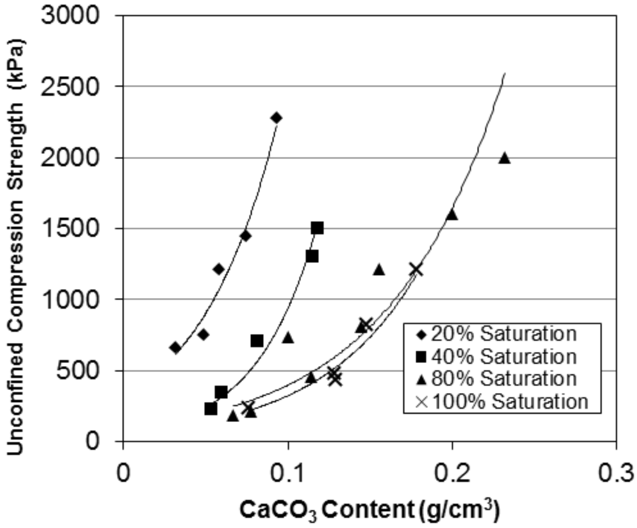
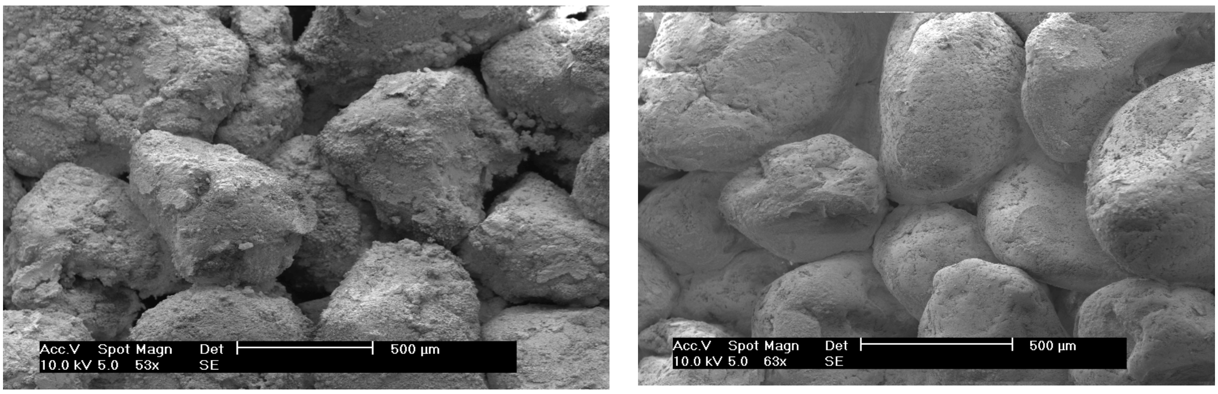


Fig. 3. UCS results of bio-cemented sand.



(a) fully saturated soil sample (b) partially saturated soil sample

Fig. 4. Formation of calcite crystals

2.5. Drained Shear Strength

Principal engineering design situations involving granular soils often exist under drained conditions due to the high permeability characteristics of the material. The stability of the geotechnical engineering structures depends mainly on the shear strength and deformation characteristics of the materials used. In this study, a series of strain-controlled consolidated undrained tri-axial tests were carried out to establish the effective shear strength parameters (cohesion, c’, and friction angle, ’) of the bio-cemented sand. All tests were conducted in accordance with the procedures set out by

Head (1998). Before carrying out the tri-axial tests, different bio-cemented soil samples were prepared by treating them at degrees of saturation of 30, 65 and 100%. The tri-axial tests started with fully saturating each treated soil specimen and this was measured by checking that the Skempton's pore water pressure parameter *B* is not less than 0.95. The soil specimens were then subjected to cell pressures of 50, 100 and 200 kPa, and an axial stress was applied to failure at a strain rate of 1 mm/minute. A sample of the obtained stress-strain behavior for the untreated and treated soil specimens at confining pressure of 50 kPa is shown in Fig. 5. It can be seen that bio-cemented soil provides higher strength and stiffness than untreated soil. Similar stress-strain behavior was also obtained at confining pressures of 100 and 200 kPa.

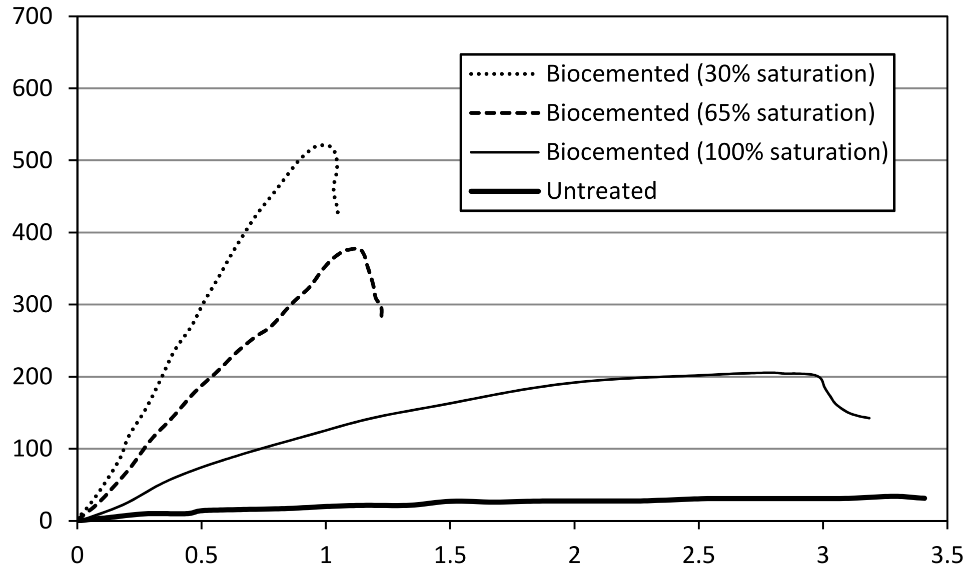
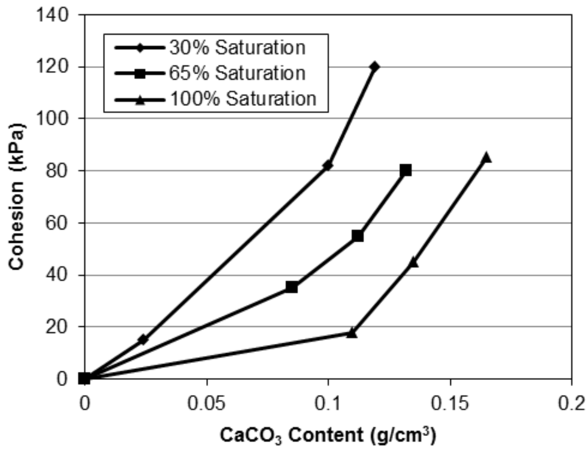


Fig. 5. Stress-strain curves of tri-axial testing for untreated and bio-cemented sands at cell pressure of 50 kPa

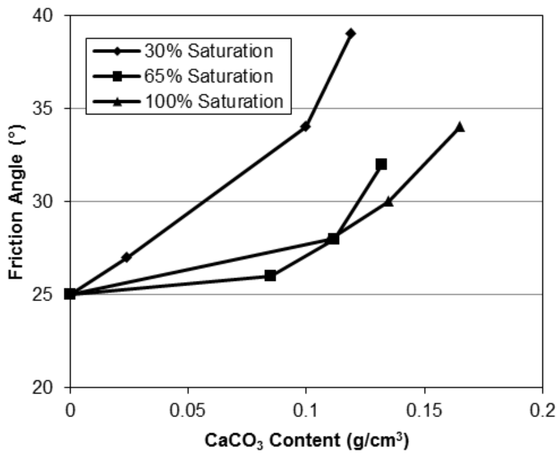
The shear strength parameters (i.e. cohesion and friction angle) were determined from the Mohr-Coulomb envelopes that were developed from the peak shear stress values obtained from the tri-axial tests and the results are shown in Fig. 6. It can be seen that the shear strength parameters of granular sands used in this study improve due to bio-cementation. Soil cohesion enhancement is mainly due to the precipitation of calcite crystals at the particle contact interface. The enhancement of friction angle suggests that density within the soil matrix escalates resulting in greater physical friction between sand particles. Samples partially saturated at 30% facilitated the greatest resistance to shear irrespective of grain size.

Important trends that exist in Fig. 6 are the significant increase in the shear strength parameters with decreasing degree of saturation, which is due to the effective precipitation of calcite formation at the particle connection points. As mentioned earlier, the produced calcite deposits of higher saturated conditions exists as small, loosely held masses on the grain surface or suspended in pore spaces, providing minimal contribution to the adhesion of the soil matrix. The practical significance of obtaining greater increase in shear strength at lower degree of saturation is an important finding, challenging past study conclusion.

The above results provide verification for MICP to be potentially used in geotechnical applications as a promising soil stabilisation technique. Subgrade and embankment are two prospective applications that can integrate MICP. Bio-grouting has the potential to reduce the cost associated with excavation by allowing engineers to stabilise and strengthen excavated weak soils, as will be described in the next section. Subgrade strengthened by MICP also has the potential to eliminate other base layers required for road construction, as the strength provided by bio-cementation emulates that of calcareous rock. These advantages reduce the amount of fill material required for roadway construction promoting sustainability and reducing expensive transport requirements.



(a) cohesion of treated soil



(a) friction angle of treated soil

Fig. 6. Results of soil parameters obtained from the tri-axial tests

CONCLUSION

The results presented in this study have established significant improvements in the shear strength parameters of poorly graded loose sands from the trialled bio-cementation process. Bio-cemented samples representative of calcareous rock have been engineered through the successful application of a microbiological process. The study was able to successfully cultivate urea hydrolysing bacteria which allowed this study to harness the metabolic pathway of the bacteria resulting in the formation of calcium carbonate precipitation throughout the soil matrix.

The effectiveness of microbial induced cementation process is significant based on reference behaviour of baseline conditions. Both permeability and shear strength of bio-cemented soils displayed results that would support MICP as a promising soil improvement technique. Findings of this study confirmed that higher strengths were obtained at lower saturation degrees, challenging the previous belief that bio-cemented soils need to be treated under full saturated conditions. This important finding indicate that optimum performance of this stabilisation process can be achieved with lower costs, making it economically viable while reducing the need for water, hence more environmentally sustainable than formerly believed. MICP is expected to be a viable alternative for engineering soil improvement applications such as slope stability, liquefiable sand deposits and subgrade reinforcement.

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