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Bio-cementation of Sandy Soil at different Relative Density

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ABSTRACT: Enzyme-induced carbonate precipitation (EICP) is a bio-inspired technique used to improve the geotechnical properties of a variety of soils. The process of EICP is triggered by plant-derived urease enzyme in the presence of calcium ion to produce calcium carbonate within the soil matrix. This study aims to evaluate the influence of relative density on the strength of bio-cemented sandy soil. The mix and compact method was adopted to treat the sandy soil. Soil samples were prepared at three different relative density (loose, medium, and dense states) and three concentrations of cementation reagent (0.25, 0.5 and 1.0 M). The unconfined compressive strength tests, calcium carbonate content and FESEM analysis were carried out on the treated soil sample. The findings showed that the unconfined compressive strength (UCS) increased with higher relative density and concentration of cementation reagent (CCR). For instance, at 0.25 M UCS value of 98, 141 and 160 kPa were obtained at loose, medium and dense state, respectively. The shows that the increase in strength of bio-cemented sandy soil was not only attributed to the calcite content formed within the soil but also the extent of the denseness of the soil. The microstructural morphology further confirms the formation of $CaCO_3$, which is partly responsible for the general improvement of strength of the sandy soil.

Keywords: Enzyme-induced carbonate precipitation, Unconfined compressive strength, relative density, sandy soil.

Abbreviations: Enzyme-induced carbonate precipitation, EICP; Unconfined compressive strength, UCS, Concentration of cementation reagent, CCR.

I. INTRODUCTION

In the field of geotechnical engineering, bio-based soil improvement methods occur either through microbial-induced calcium carbonate precipitation (MICP) and enzyme-induced calcium carbonate precipitation (EICP). The soil improvement process is achieved through the precipitation of calcium carbonate ($CaCO_3$) crystals as a result of the biochemical reaction that occurs within the soil matrix. Both processes have been found promisingly to be environmentally friendly when compared to traditional soil improvement methods [1,2]. As both processes rely on the urea hydrolysis metabolic pathway, the significant difference is that MICP uses a non-pathogenic organism, while EICP utilises plant-derived urease enzyme to initiate the biochemical process [3]. The significant advantage of EICP is the avoidance of the complex processes involved in bacteria cultivation and storage, which frequently require a sterile environment. Furthermore, since the small size of the urease enzyme makes it more soluble, it can undoubtedly be used to treat finer-grained soils such as silt and clay since it easily penetrates through the pores of the soil [4].

The mechanism of $CaCO_3$ precipitation by urea hydrolysis can be categorised into two stages: (1) urea hydrolysis and (2) $CaCO_3$ precipitation [5, 6].

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

$$\mathrm{Ca^{2+} + CO_2^{2-} \rightarrow CaCO_3} \quad (2)$$

Quantitatively, during the urea hydrolysis stage, 1 mol of urea $CO(NH_2)_2$ is hydrolysed to produce 1 mol of carbonate (CO_3^{2-}) and 2 mol of ammonium (NH_4^+) ions. The ammonium ions increase the local pH, thereby creating a favourable environment for calcite precipitation. During the calcite ($CaCO_3$) precipitation stage, the introduced calcium ions (Ca^{2+}) derived from calcium chloride ($CaCl_2$) in the cementation solution reacts with the carbonate ions (CO_3^{2-}) to form 1 mol of calcium carbonate ($CaCO_3$) crystals. The calcium carbonate formed is responsible for improving the geomechanical properties of the soil due to its bonding and densification effects [7, 8]. Even though the application of bio-cementation in the soil is still limited to small scale experiments, it demonstrates some prospects in reducing permeability and increasing strength and stiffness, as shown in laboratory experiments [9,10]. The potential application of bio-cementation of soils includes permeability reduction, erosion control, slope stability, and mitigation of liquefaction [11,12].

Factors that affect the performance of bio-based soil improvement can be divided into biological and geotechnical factors. Some of these factors include concentration of cementation reagent, bacteria/urease concentration, pH, temperature, geometric compatibility, number of cycles of treatment, the density of soil, size and shape of the soil particles [13–16]. For instance, in a study conducted by [17], the effect of grout solution content, curing time, the CCR, and urease enzyme on the process of enzymatic calcium carbonate precipitation was analysed. The findings revealed that the stiffness and strength of the treated soil increased with an increase in grout solution content and a higher curing period. However, the efficiency of the treatment process tends to be better at lower concentrations of the cementation solution. Other studies have also explored the effect of some of these biological factors on the performance of bio-cementation [16, 18, 19].

Several studies have investigated the effect of relative density on the bio-cementation of sandy soil through the use of microbes to serve as the source urease enzyme [20–22]. The treatment process involves the injection of the bacteria solution followed by an injection of several cycles of cementation solution. The finding showed that the formation of calcium carbonate decreases with an increase in relative density. Furthermore, the distribution of $CaCO_3$ precipitates is more uniform at lower relative density (loose state) when compared to that at a higher relative density (medium and dense state) [23]. This could be attributed to the porous nature of the soil at a loose state that allows both bacteria and cementation solution to flow easily through the pore spaces of the soil. The issue of clogging at the point of injection was a significant challenge and the MICP method require a longer time to achieve the minimal cementation.

Although, numerous studies have been conducted to determine some of the effects attributed to these factors on the performance of EICP, very few have considered the effect of the geotechnical based factors on the effectiveness of the treatment process. Therefore, this study aims to investigate the effect of relative density on unconfined compressive strength of EICP treated sandy soil.

II. MATERIALS AND METHODS

Soil: The soil used in this study was sourced from Stulang Laut Beach, Johor Bahru in Peninsular Malaysia. The physical properties of the soil were carried out based on BS 1377 (1990).

EICP treatment solution: The EICP treatment solution comprised of a mixture of urea, $CaCl_2$, and urease enzyme having a purity level of 99.5%, all purchased from the Fisher Scientific in Malaysia. The urease enzyme was produced from Canavalia ensiformis (jack bean) and comes in a powdered form. The EICP treatment solution was prepared by mixing urea and calcium chloride dehydrate at various molarities with the urease enzyme. Table 1 shows the composition of the EICP solution at various molarities. The constituents were mixed with distilled water, ensuring all the chemicals were completely dissolved before used in the treatment process.

Table 1: Composition of cementation reagents.

Concentration (M)	0.25	0.5	1.0
Urease enzyme (g/L)	3	3	3
Urea (g/L)	15	30	60
$CaCl_2$ (g/L)	27.8	55.5	147

Soil Treatment and testing: This research followed the technique of mix and compact to prepare the soil samples for the unconfined compressive strength (UCS) test. The soil specimen were prepared at various relative density (loose, medium dense, and dense states) and around 5% of the EICP solution was mixed with the soil before dividing into three portions. The mixture was then lightly compacted into a PVC split mould to achieve a sample size of 38 mm in diameter by 76 mm in height. The samples were then left to cure for three days at ambient room temperature. At the end of each curing period, the soil specimen were carefully removed from the mould and placed in inside an oven at 50℃ until is completely dried. The oven-dried sample was then tested for the unconfined compassion strength at a constant rate of 1.00 mm/minute. Fig. 1 illustrates the biocementation process. Following the UCS tests, calcite content was determined using the gravimetric acid washing method based on the procedure outlined by [8]. FESEM was carried out to determine the morphological and microstructural features of the treated soil.

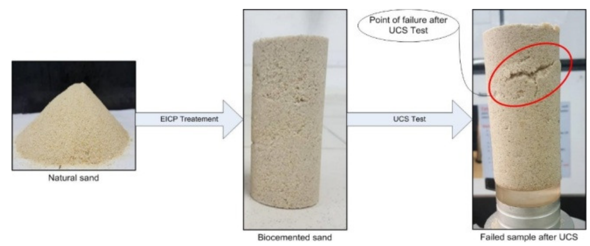


Fig. 1. The pictorial illustration of the biocementation process.

III. RESULTS AND DISCUSSION

Physical Properties: The physical properties of the soil are depicted in Table 2, while the result of the sieve analysis of the soil is shown in Fig. 2.

Table 2: Physical Properties of the soil used in the study.

Soil Properties	Values
Specific Gravity	2.66
D10	0.13
D30	0.18
D50	0.23
D60	0.26
Cu	2
Cc	0.96
emin	0.708
emax	1.302
Classification	Poorly graded Sand
pH	6

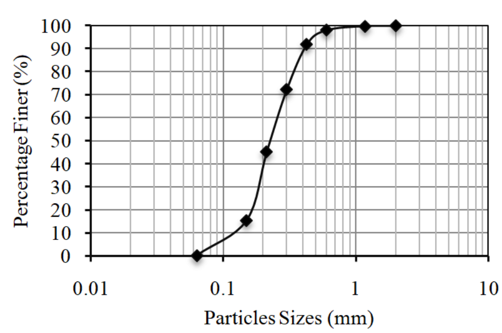
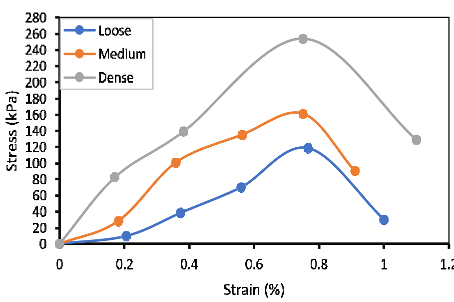


Fig. 2. The particle size distribution of the soil understudy.

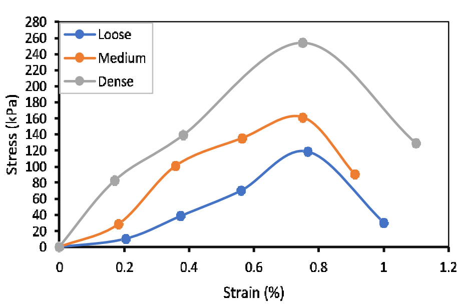
Unconfined compressive strength and FESEM images of EICP treated sandy soil: The standard test used to ascertain the effectiveness of bio-cementation of soil is the UCS test [25, 26]. However, the effectiveness of testing biotreated soils is affected by several factors, including the extent of denseness, urease content, and the concentration of cementation reagent, curing condition, and pH. In this study, the relative density at different concentrations of cementation reagent was considered. Fig. 3 shows the variation of the UCS value with relative density at different concentrations of cementation reagent. When the CCR was 0.25 M, the lowest UCS value of 98 kPa was obtained at the loose state while at the medium state, the strength increased to 161 kPa showing a 30% increase when compared with strength at the loose state.

Furthermore, at a dense state, the strength increased to 160 kPa indicating an 11% and 39% increase when compared to the strength at the medium and loose state, respectively. At 0.5 M, the gained strength followed a similar pattern. The UCS at loose, medium and dense states were 118, 161 and 254 kPa, respectively. A similar trend was observed at the CCR of 1 M. Generally, there was an increase in the UCS value with higher density at all concentrations of cementation reagent. This is also similar to the finding by [4], indicating that the strength of the mechanism of bio-cemented soil was not only governed by the amount of precipitation but also due to the particle parking.

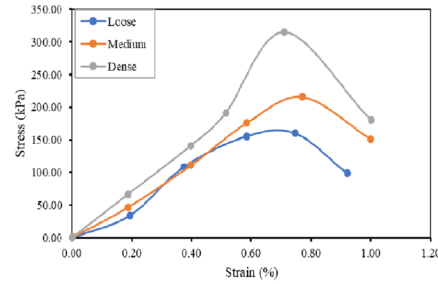
Nevertheless, the UCS values at a concentration of the cementation reagent of 1.0 M were higher when compared to 0.5 M. Similarly, the values obtained at 0.5 M were higher compared to that at 0.25 M, irrespective of the relative density of the soil. For instance, at a dense state, the strength at 0.25 M, 0.5 M, and 1.0 M were 160, 253 and 314 kPa, respectively. This represents a 36% increase in the strength value between 0.25 and 0.5 M and similarly, a 19% increase in strength between 0.5 and 1.0 M. The increase in strength may be attributed to a higher amount of calcite formed at the higher concentration of the cementation reagent [27].



(a)



(b)



(c)

Fig. 3. Variation of UCS value with relative density at CCR (a) 0.25 M (b) 0.5 M and (c) 1.0 M

Fig. 4 shows the FESEM images for both natural and bio-cemented soil samples. Fig. 4(a) depicts a sparse texture having no evidence of calcium carbonate precipitation on either the surface or between the soil particles. In contrast, Fig. 4(b) shows the formation of agglomerated binding material (calcite) at the surface of the soil particles, which is partly responsible for the strength gained as a result of the treatment process.

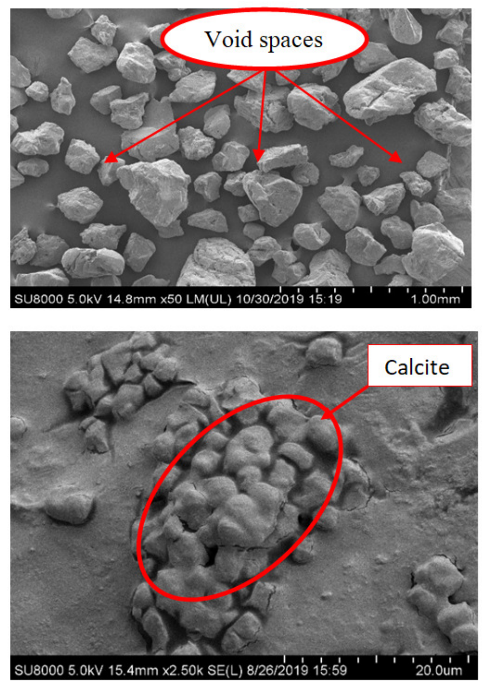


Fig. 4. FESEM images both the (a) Natural and (b) biocemented soil sample.

IV. CONCLUSION

Based on the laboratory work conducted in this research to assess the effect of relative density on the UCS of bio-cemented sandy soil, the key findings drawn from the experiment are follows:

1. The strength of biotreated soil was governed by both the calcite content and particle parking.
2. A higher CCR led to higher strength values irrespective of the relative densities.
3. The FESEM image further buttress mechanism calcium carbonate precipitation within the soil matrix.

V. FUTURE SCOPE

From the study conducted, EICP can be used to improve the strength of sandy soil. However, more experiment needs to be done to ascertain the durability of the bio treated soil.

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Conflict of Interest. The authors declare that they have no conflict of interest.

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