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TEMPERATURE EFFECTS ON THE STRENGH PROPERTIES OF MICROBIALLY STABILIZED RESIDUAL SOIL

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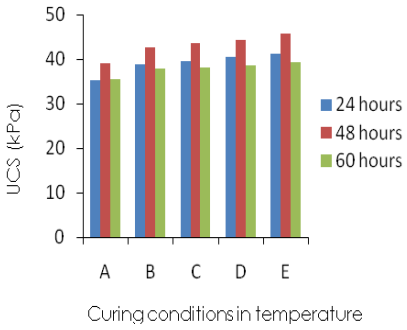
Graphical Abstract



Abstract

Microbially Induced Calcite Precipitation (MICP) is a rather new technology that has shown greater potential in geotechnical engineering applications. The technique utilizes the concept of microbial involvements in carbonate precipitation within the soil matrix that lead to the improvement in strength and stiffness of the soil. This paper evaluated the effects of temperature variations on the performance of microbial calcite precipitations in residual soil. The soil specimens were cured under different temperature conditions; that are atmospheric temperature, 40, 45 and 50°C. Shear strength, pH and amount of calcite precipitated were determined for each curing condition. A bacterial concentration of 1×10^5 cfu/ml and 0.5 M concentration of the cementation reagents were used for the study. The results indicated a general increase in strength with increase in curing temperature; which is an indication of temperature influence in bacterial activity. The results so far obtained also revealed that the higher the amount of calcite precipitated the more the strength improvement up to 48 hours treatment duration; after which increase in calcite content does not results in the increase in strength.

Keywords: Temperature variation; strength; residual soil; pH; carbonates precipitation

1.0 INTRODUCTION

The traditional and most frequently used techniques in soil improvement includes among many others compaction, soil replacement, applications of chemical admixtures and grouting method to modify the engineering properties of soil in order to serve an intended engineering purpose. Though, most of these techniques have proved successful in improving the engineering properties of soils, some are found to be detrimental to environmental safety. This is because they usually require high amounts of energy, costs, have limitations with regards to treatment range and require materials which have considerable impact on the environment [1, 2]. However, it was reported by Dejong [1] that around $ 6 billion is being spent every year on over forty thousand (40,000) soil improvement projects all over the world. And majority of these soil improvement techniques utilize mechanical energy and/or man-made materials, both of which require substantial energy for material production and/or installation. As such the need for new, sustainable and environmentally friendly method for soil improvement is necessary.

Meanwhile, a new technique that utilizes biological process within the soil, to produce calcium carbonate is technically known as Microbially Induced Calcite Precipitation (MICP). The concept involves natural process of urea hydrolysis by some microorganisms that are native in soil and groundwater to produce urease enzyme that lead to the formation of calcite

[3]. Most Bacillus species can trigger urea hydrolysis by producing urease enzymes [4]. The calcium carbonate is responsible for cementing and clogging the soil particles together, thereby increasing the strength and stiffness and reducing the permeability of the soil. This technique has drawn the attention of many geotechnical engineers and its application in soil improvement has been demonstrated in many researches with interesting findings [5-8]. The MICP process can be a viable alternative technique that improve soil supporting new and existing structures and in many geotechnical engineering applications such as liquefiable sand deposits, slope stabilization, and subgrade reinforcement [9].

The process involved using bacteria that are capable of producing urease enzyme which is required for decomposing urea into ammonium (NH_4^+) and carbonates (CO_3^{2-}) ions through a chemical process known as hydrolysis of urea. The ammonium ions increase the local pH, thereby creating a favourable environment for calcite precipitation. The carbonate ions react with the calcium ions from the supplied calcium chloride to form the required calcium carbonate ($CaCO_3$). The chemical reactions involved are shown in equation 1 and 2.

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

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \quad (2)$$

The amount of calcium carbonate crystals that would be precipitated during the MICP process directly influence some engineering properties of the soil treated such as strength, stiffness and permeability. Likewise, the distribution of the carbonate crystals within the soil pores and amount precipitated are also influenced by some properties of the soil such as particle sizes, mineralogy, insitu saturation, density, shape and texture [10, 11]. Most biomediated soil improvement processes are done without giving much attention to temperature variations effects. Though, temperature has considerable influence on the urease activity and the subsequent calcite production. It was found that urease activity is very minimal at temperature below 5°C [12]. However, it was reported by Whiffin [13] that urease activity in *Sporosarcina pasteurii* increased proportionally with increase in temperature between 25 and 60°C. The urease activity reached an optimum value at 70°C.

Therefore, this paper intends to evaluate the effects of temperature on the calcite formation within the soil matrix structure and the subsequent strength improvement of a microbially treated residual soil.

2.0 MATERIALS AND METHOD

2.1 Soil Specimen

The soil sample used for this study is a tropical residual soil which is classified as Gravelly silt of intermediate plasticity (MIG) based on British Soil classification System (BSCS) and was collected from a site at University of Technology Malaysia UTM, Johor Campus. Figure 1 shows the particle size distribution curve for the sample and Table 1 present the Index properties of the soil.

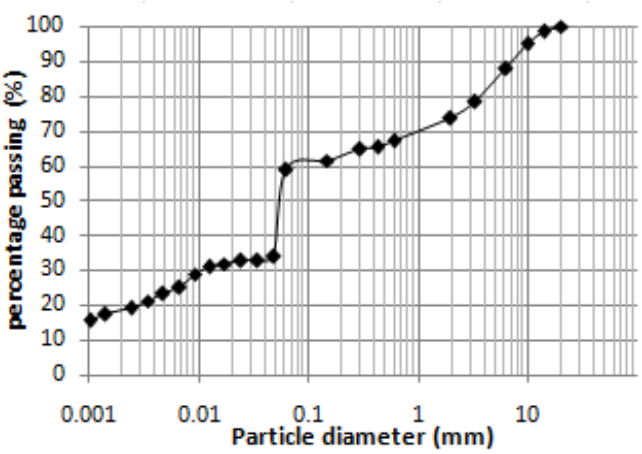


Figure 1 Particle size distribution curve of the sample

2.2 Bacteria and Cementation Reagents

The urease active strain of *Sporosarcina pasteurii* (ATCC® 11859™) was used in this study. The strain was cultivated in a yeast extract–based medium of 20 g yeast extract, 10 g ammonium sulphate in a 1 Litre 0.3 M Tris buffer solution of pH 9.0. After 48 hours incubation at 30 °C, the culture was harvested and stored at 4 °C prior to use. Bacteria concentration of 1×10^5 cfu/ml was used in the study. The cementation reagents consist of 3 g nutrient broth and 0.5 M concentrations of $CaCl_2$ and urea.

Table 1 Index properties of the soil sample

Properties	Description
Gravel	27%
Sand	19%
Silt	40%
Clay	14%
Liquid limit	57.58%
Plastic limit	44.38%
Specific gravity	2.60
MDD	1.402Mg/m^3
OMC	26.5%
Classification(BSCS)	MIG
UCS (kPa)	32.3

2.3 Sample Preparations

To prepare the soil specimens, air dried residual soil was first mixed with a culture medium containing the urease-producing microorganism (*Sporosarcina*

pasteurii) to attain a moisture content corresponding to the optimum of 26.5%. The soil specimens were cured under different temperature conditions; that are atmospheric temperature, 40, 45 and 50°C. Hence, one specimen was compacted immediately after mixing without curing to serve as control. The cured soil specimens were then compacted into the prefabricated steel mould to a dry density of 1.402 Mg/m^3 (maximum dry density). The soil specimens were sandwiched between two filter layers (clean gravel) to avoid turbulent inflow and clogging at the inlet.

3.0 RESULTS AND DISCUSSION

3.1 Effect of curing conditions (temperature) and treatment durations

Temperature effect and bacteria concentrations have been reported among the environmental factors that greatly influence the microbial calcite precipitations [14]. Hence, the effects of curing temperature and bacteria concentrations on the calcite precipitated and the subsequent increase in the strength of the residual soil have been evaluated. Figure 2 presents the relationship between the strength (UCS) and different curing conditions under different treatment durations. The result shows a general increase in strength as the curing temperature increases for all the treatment durations; this is in agreement with the findings of [13] which stated that urease activity increases proportionally with increase in temperature up to 70°C. Moreover, treatment of 48 hours indicated higher strengths above 24 hours duration. Shear strength improvement of 27% relative to untreated sample was recorded for 24 hours and another 13% in the second 24 hours (40% at 48 hours). Hence, at 60 hours the strength decreases; possibly the calcite precipitated at 48 hours were enough to fill all the soil voids for the strength improvement. Therefore, more calcite will not add to the strength and longer treatment duration beyond 48 hours will only results in soaking the sample thereby weakening it. Considering the 48 hours treatment duration that produces higher strength improvement of 40%; it can be deduced that MICP was most effective within 48 hours as also revealed by [15].

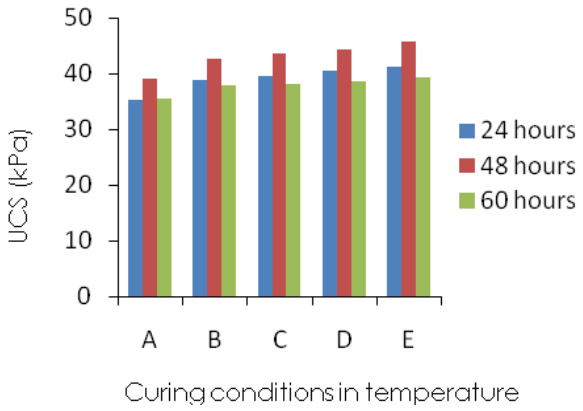


Figure 2 Relationship between UCS and curing conditions (A: No curing; B: Atmospheric temperature; C: 40°C; D: 45°C; E: 50°C)

3.2 Correlation between calcium carbonate content and UCS

Figure 3 shows the correlation between calcite contents and curing conditions at different treatment durations. The increase in curing temperature is directly related to the increase in calcite content for all the treatment durations. This indicated that as the temperature increases the bacteria becomes more active to precipitates more calcites; providing more binding effect between the soils particles thereby improving the strength. It was also observed that for 60 hours treatment durations; despite the increase in calcite contents the strength decreases. This may be in line with the suggestion by [16, 17] that long treatment duration in the presence of calcium ions may lead to local super-saturation and heterogeneous calcite precipitation on the bacteria cell wall. This would finally result in cell death and weaken the effectiveness of the MICP process.

3.3 Variations of pH over the treatment durations

Figure 4 presents the pH variations over the treatment durations of 60 hours. The results indicated a continuous increase in the pH for all the treatment durations. The first measured pH was slightly above 7; which is an indication of very little ammonium ions productions at the initial stage of the treatment. The urea hydrolysis induced by the bacteria results in the production of ammonium ions that subsequently increased the pH of the soil environment. The pH increase creates an ideal environment for the calcite precipitations [18].

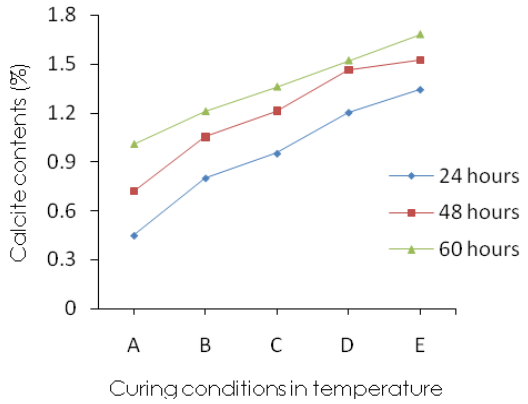


Figure 3 Correlation between calcite contents and curing conditions (A: No curing; B: Atmospheric temperature; C: 40°C; D: 45°C; E: 50°C)

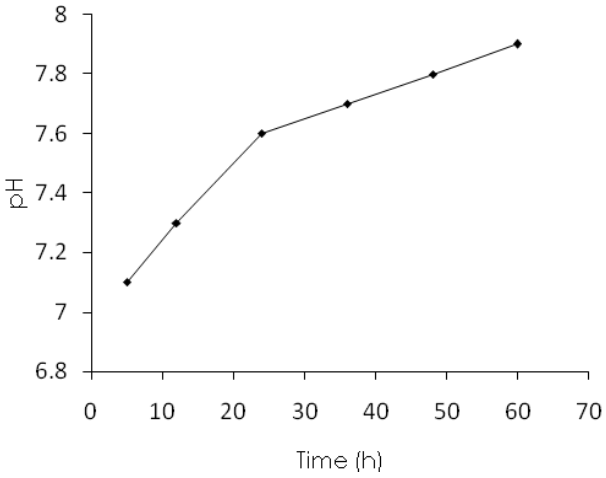


Figure 4 Variations of pH with treatment duration

4.0 CONCLUSION

General increase in strength with the increase in curing temperatures for all the treatment durations was observed. This revealed that increase in temperature facilitates the bacterial activity to precipitates more calcite for strength improvement. The longer the treatment duration the more the calcite contents increase (up to 48 hours) causing more binding effects between the soils particles; thereby increasing the strength. Hence, 48 hours treatment duration that produces 40% improvement in strength was found to be the most effective. Hence, the continuous increase in the pH over the treatment durations is an indication of the bacterial activity to hydrolyze urea for calcite precipitations.

Acknowledgment

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