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Stress-deformation and compressibility responses of bio-mediated residual soils

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ABSTRACT

Bio-mediated soil improvement technique has attracted increasing interest from geotechnical engineers in recent years. This paper investigates the stress-deformation and compressibility responses of bio-mediated soil at laboratory scale. A typical residual soil was subjected to microbially-induced calcite precipitation (MICP) under various treatment durations, concentrations and flow pressures of cementation reagents. The experimental results showed that the stiffness and peak strength of soil were significantly improved by the MICP treatment. The amount of calcite precipitated showed a linear correlation with recompression index (C_r), reasonable correlations with peak strength (τ_p) and total settlement (S_c), but a poor correlation with compression index (C_c). Under a high applied stress (exceeds the yield stress of soil), the MICP treatments become ineffective in improving the compressibility characteristics of soil attributed to fracturing of calcite bonds. Cementation reagent with a low flow pressure (i.e. 0.2 bar) contributed to more favorable stress-deformation and compressibility responses than those of high flow pressures.

1. Introduction

Bio-mediated soil has recently emerged as a new sustainable technique of soil improvement. The technique takes advantages of natural bio-activities, technically termed as microbially induced calcite precipitation (MICP), to improve engineering properties of soils. The MICP process has also shown promising applications in other construction materials, i.e. improvements of strength (Siddique et al., 2008; Raijiwala et al., 2009) and durability (De Muynck et al., 2008; Achal et al., 2011) of concrete/mortar, and durability of brick (Sarda et al., 2009).

In general, MICP can be achieved by urea hydrolysis, aerobic oxidation, denitrification, sulfate reduction, etc. van Paassen et al. (2010) suggested that urea hydrolysis possesses the highest calcite conversion rate compared to other studied processes. Urea hydrolysis refers to a chemical reaction where urea ($CO(NH_2)_2$) is decomposed by urease enzyme that can be either supplied externally (Nemati and Voordouw, 2003) or produced in situ by urease-producing microorganism (DeJong et al., 2006; Whiffin et al., 2007; Martinez et al., 2011). The latter process requires urease positive type bacteria, i.e. genera *Bacillus*, *Sporosarcina*, *Spoloactobacilus*, *Clostridium* or *Desulfotomaculum* (Kucharski et al., 2008). The corresponding chemical reaction involves 1 mol of urea decomposes into 2 mol of ammonium:

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

The release of ammonium (NH_4^+) increases pH, and eventually creates an ideal environment for calcite precipitation with the presence of calcium ion (Ca^{2+}) from the supplied calcium chloride:

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

The calcite ($CaCO_3$) precipitated is responsible for improving inherent engineering properties of soil through biocementation and bioclogging. Biocementation is defined as an improvement of soil strength by production of particle-binding materials through microbial means, while bioclogging is a reduction of hydraulic conductivity of soil or porous rock by pore-filling materials generated by microbial processes (Ivanov and Chu, 2008).

Studies pertaining to the topic of bio-mediated soil improvement had been reported by numerous researchers. DeJong et al. (2010) provided an overview of potential applications of this new technique in improving engineering properties of soil. Various microscopy techniques were used to quantitatively assess the distribution of calcite during the soil improvement. Qian et al. (2010) used three types of urease-producing bacteria to consolidate sand grains. They found that the precipitation program was essential for

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obtaining an effective cementation in the sand body. Al Qabany et al. (2012) investigated the potential factors affecting the MICP in sand. They concluded that high chemical efficiency MICP can be achieved by supplying a low input rate (less than 0.042 mol/l/h) of urea and calcium chloride. A number of studies focused on methods of fixing and distributing bacteria in sand. Harkes et al. (2010) found that injection of undiluted bacteria suspension, followed by one pore volume of high salinity fixation fluid (50 mM of calcium chloride) could retain almost all bacteria suspension in the sand bed. Martinez et al. (2011) found that stopped-flow injection method (injection of 1.5 pore volume of reagent, followed by 2.5 h of rest period) offered a more uniform cementation than continuous injection. Cheng and Cord-Ruwisch (2012) adopted a new surface percolation method for in situ placement of bacteria and cementation reagent. They successfully distributed the bacteria uniformly over the entire length of an 1 m sand column. Recently, Martinez et al. (2011) attempted to upscale the bio-mediated treatment process for in situ implementations. They concluded that continued research must address several challenges associated with the field implementations such as soil and pore fluid interactions, bioaugmentation versus biostimulation of microbial communities, controlled distribution of mediated calcite precipitation, and permanence of the cementation.

The state of the art researches on bio-mediated soil improvement mainly focus on shear strength improvement (biocementation) and hydraulic conductivity reduction (bioclogging). Through the MICP process, calcite minerals are found predominantly near the silica sand grain contacts (Martinez and DeJong, 2009). These calcite minerals strengthen particle bonds, and hence increase the strength and stiffness of loose sand deposits (Martinez and DeJong, 2009; Mortensen, 2012). Furthermore, without considering the bonding/cementation effects created by the calcite minerals, DeJong et al. (2010) found that densification of soil alone could also alter the soil behavior. Nemati et al. (2005) investigated the plugging behavior of porous medium for soil hydraulic conductivity reduction. Ng et al. (2013) compared the shear strength improvement and hydraulic conductivity reduction between bio-mediated sand and residual soil. They concluded that the improvements of bio-mediated residual soil were comparable to those of sand specimens. Al Qabany et al. (2011) correlated the stiffness of sand with calcite content. An increase in calcite content yielded a higher S-wave velocity, and hence a higher stiffness.

Depending on functional requirements of a structure, settlement deformation is often regarded as one of the most important design criteria in geotechnical engineering practices. Engineering properties such as stress-deformation and compressibility responses of bio-mediated soil have rarely been investigated in the published literature. Understanding of these properties is essential for promoting potential applications of this exciting soil improvement technique in solving real-life geotechnical problems. This paper provides an insight into the stress-deformation and compressibility of bio-mediated soils through unconfined compression tests and one-dimensional consolidation tests, respectively. Three treatment variables, i.e. treatment duration, concentration and flow pressure of cementation reagents are considered in the present study to investigate their effects on the compressibility responses of bio-mediated soils.

2. Materials and methods

2.1. Urease-producing bacteria

The urease-producing bacterium used in this study was *Bacillus megaterium ATCC 14581*. The bacterium was cultivated at pH 7 under aerobic batch conditions in a sterile culture medium of 5 g/l peptone, 5 g/l sodium chloride, 2 g/l yeast extract, and 1 g/l beef extract. Incubation was performed in a shaking incubator at 200 rpm under a constant temperature of 37 °C. The *B. megaterium* was grown to early stationary phase before harvesting at a concentration of approximately 1×10^8 cfu/ml.

Table 1
Properties of residual soil.

Properties	Values
Grain size	0% gravel, 38% sand, 43% silt, 19% clay
Liquid limit (LL)	40.4%
Plastic limit (PL)	24.9%
Maximum dry density (MDD)	1688.5 kg/m^3
Optimum moisture content (OMC)	16.6%

2.2. Cementation reagents

Cementation reagents serve as important ingredients for promoting calcite precipitation. The cementation reagents used in the present study essentially contained desired concentrations of urea and calcium chloride, and 3 g/l of nutrient broth supplement.

2.3. Soil material

The soil material used in the present study was a typical silty residual soil extracted from a site in Kuala Lumpur, Malaysia. The soil has particle sizes ranging from clay fraction to 2 mm. Rebata-Landa (2007) suggested that the optimum range of grain size for the bio-cementation process is between 50 and 400 μm as bacterial activity cannot take place in very fine soils, while large amounts of calcites are required to promote effective improvements in very coarse soils. In the present study, 32% of the residual soil particles fall within the range of 50–400 μm. Table 1 tabulates the physical properties of the soil.

2.4. Apparatus setup

Fig. 1a shows the schematic diagram of the apparatus setup for the MICP treatments. The apparatus consisted of a steel mold of 50 mm in diameter and 170 mm in length (Fig. 1b), an air compressor, a pressure tank, and an effluent collector. The air compressor and pressure tank was used to regulate desired flow pressures of the cementation reagent percolating through the soil specimen.

2.5. MICP treatment

An adequate amount of water and the incubated bacteria were first mixed with air-dried soil mediums and compacted into the prefabricated specimen mold at a dry density of about 1519 kg/m^3 (90% of maximum dry density). Prior to compaction, grease was applied on the inner surface of the mold to function as a lubricant during specimen extrusion process at the latter stage. The soil was sandwiched by two filter layers (gravel) of 10 mm thick each to avoid turbulent inflow and clogging near the inlet of the specimen. The specimen mold was then clamped vertically and connected to the apparatus setup as illustrated in the Fig. 1a. Cementation reagent was allowed to percolate through the soil specimens at room temperature (ranging from 25° to 30°) for a designated duration. Upon completion of the treatment, the soil was extruded from the steel mold. A portion of the soil was fitted into a standard oedometer ring of an identical diameter (50 mm). Consolidation test was then carried out in accordance with the ASTM D2435 – 04 (ASTM, 1999) with incremental loadings of 25 kN/m^2, 50 kN/m^2,