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Review

Biological process of soil improvement in civil engineering: A review

Murtala Umar*, Khairul Anuar Kassim, Kenny Tiong Ping Chiet

Department of Geotechnics and Transportation Engineering, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor, 81310 UTM, Malaysia

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A B S T R A C T

The concept of using biological process in soil improvement which is known as bio-mediated soil improvement technique has shown greater potential in geotechnical engineering applications in terms of performance and environmental sustainability. This paper presents a review on the soil microorganisms responsible for this process, and factors that affect their metabolic activities and geometric compatibility with the soil particle sizes. Two mechanisms of biomineralization, i.e. biologically controlled and biologically induced mineralization, were also discussed. Environmental and other factors that may be encountered in situ during microbially induced calcite precipitation (MICP) and their influences on the process were identified and presented. Improvements in the engineering properties of soil such as strength/stiffness and permeability as evaluated in some studies were explored. Potential applications of the process in geotechnical engineering and the challenges of field application of the process were identified.

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1. Introduction

Recent studies on applications of bio-mediated soil improvement method have proved the viability of the approach for effective performance and environmental sustainability. The promising outcomes of these studies have shown greater potential of exploring a wider application of the technique in geotechnical engineering. Bio-mediated method of soil improvement has been considered as an inventive and new approach in geotechnical engineering that can be utilized to prevent liquefaction and landslide in loose sand which usually results in foundation deformation and/or failure (Alvarado, 2009). The great promise of the use of biological treatments has been demonstrated in many applications, such as improving the shear strength and decreasing the permeability of soils (Whiffin et al., 2007; Ivanov and Chu, 2008; Harkes et al., 2010; van Paassen, 2011), improvement in strength and durability of concrete and mortar, remediation of cracks in buildings (Qian et al., 2010; Achal et al., 2013), improvement in engineering properties of soil, and cementation of sand column (Achal et al., 2009a; Dhami et al., 2013).

Bio-mediated method of soil improvement generally refers to the biochemical reaction that takes place within a soil mass to produce calcite precipitate to modify some engineering properties of the soil (DeJong et al., 2010). Meanwhile, utilizing the interdisciplinary knowledge of civil engineering, chemistry and microbiology to alter the soil engineering properties in the subsurface has emerged recently (Whiffin et al., 2007; Ivanov and Chu, 2008; Mitchell and Santamarina, 2005; DeJong et al., 2010). The technique utilizes soil microbial processes, which is technically referred to as microbially induced calcite precipitation (MICP), to precipitate calcium carbonate into the soil matrix. The calcium carbonate produced binds the soil particles together (thereby cementing and clogging the soils), and hence improves the strength and reduces the hydraulic conductivity of the soils. MICP can be a practicable alternative for improving soil-supporting both new and existing structures and has been used in many civil engineering applications such as liquefiable sand deposits, slope stabilization, and subgrade reinforcement (DeJong et al., 2006; Cheng et al., 2013).

It was revealed that microorganisms influence the formation of fine-grained soils and change the behavior of coarse-grained soils such as strength and hydraulic conductivity. They also facilitate chemical reactions within a soil mass, promote weathering and change the chemical and mechanical properties of specimens after sampling. Hence, the effects of these microorganisms on mechanical properties of soils are still not fully discovered in geotechnical engineering field (Mitchell and Santamarina, 2005). Though it was understood that there are more microorganisms in the subsurface

* Corresponding author. Tel.: +60 166277680.
E-mail address: mumar.civ@buk.edu.ng (M. Umar).
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than on the ground, and studies of many years have proved the relevance of biological activities in influencing soil behavior, less work has been done in exploring the importance, relevance, usefulness and application of biology in geotechnical engineering. Meanwhile, it is expected that a clear understanding of the impact of microorganisms and biological activity on soil behavior can lead to proper soil characterization and/or classification and even alternative geotechnical engineering solutions. This paper reviews the concept of biomineralization and its applications in improving the engineering properties of soils.

2. Soil microorganisms

Soil contains more genera and species of microorganisms than other microbial habitats. This may be due to the fact that it contains a lot of nutrients and usually retains some liquid within its pore spaces. Some species of these microorganisms are present in large numbers while some are otherwise not, probably because the factors necessary for the survival and growth of these microorganisms are not evenly distributed naturally across the depth of the lithosphere. Microorganisms are highly adaptable to varying conditions both genetically and physiologically, because they have been in existence for over 3.5 billion years (Stotzky, 1997).

There are approximately 10^9–10^{12} organisms per kilogram of a soil mass close to the ground surface. Among the microorganisms present in soil are bacteria, archaea and eukarya. Some of the important characteristics of bacteria and archaea include simple cell structure without membrane-enclosed nucleus, more than one chromosome and distinct chemical composition which are more pronounced than structure. Identification, characterization and classification of microorganisms are usually achieved using the type of cell wall, shape, nutrients, type of biochemical transformation, and DNA and RNA sequences (Woese et al., 1990; Ehrlich, 1998; Chapelle, 2001).

According to Mitchell and Santamarina (2005), the most abundant microorganisms in soils are bacteria. In order to withstand adverse environmental conditions, some bacteria make spores. They have a cell diameter ranging from 0.5 μm to 3 μm and shape of nearly round, rod like or spiral. Madigan et al. (2008) revealed that bacteria can survive in an environment of low to high acidity and/or salinity. They can also survive at very low to high temperatures ranging from below freezing to above boiling points and withstand very high pressures. Majority of bacterial cells have a negative surface charge for groundwater pH values between 5 and 7, which is typical for near surface soils; and the negative surface charge decreases with increasing concentration and valence of ions in the pore fluid (Chapelle, 2001).

Because the bacteria are native to the earth, they may not likely cause any environmental hazard in future (Fritzges, 2005). A number of bacteria species are capable of producing urease enzyme and are used in bio-mediated soil improvement technique, including genera *Bacillus*, *Sporosarcina*, *Sploactobacilus*, *Clostridium* and *Desulfotomaculum* (Kucharski et al., 2006).

The activity of urease-producing microorganisms can be divided into two different classes based on their response to high presence of ammonium. The first group includes the bacteria whose urease activity is not repressed due to high ammonium concentration, as indicated in Table 1. While the second group includes *Bacillus megaterium, Alcaligenes eutrophus, Klebsiella aerogenes* and *Pseudomonas aeruginosa* (Kaltwasser et al., 1972; Friedrich and Magasanik, 1977), whose urease activity is repressed by high ammonium concentrations. Therefore, microorganisms whose urease activity are not repressed by the high content of ammonium are preferred in bio-mediated soil improvement since high concentrations of urea are hydrolyzed in the process (Whiffin, 2004).

Table 1
Microorganisms whose urease activity is not repressed by NH_4^+ (Whiffin, 2004).

Microorganisms	High activity	Not repressed by NH_4^+	Not pathogenic or genetically modified
Sporosarcina pasteurii	Yes	Yes	Yes
Proteus vulgaris	Unknown	Yes	Moderately
Proteus mirabilis	Unknown	Yes	No
Helicobacter pylori	Yes	Yes	No
Ureplasmas (*Mocllicutes*)	Yes	Yes	No

Hence, all microorganisms are found to be good for biomineralization applications because of their urease activity; they must also be safe for the environment during and after the treatment process. Therefore, urease-producing bacteria for bio-mediated applications should not be pathogenic, genetically being modified or enclosing any exchangeable elements that may enhance the pathogenicity of environmental microbes.

According to Burne and Chen (2000), urea hydrolysis generally follows a series of chemical reactions that lead to the formation of ammonia (NH_3) and carbon dioxide (CO_2). The chemical reaction is presented in Eq. (1). The hydroxyl ions (OH^-) generated from the conversion of ammonia to ammonium result in the increase in local pH value that leads to the decomposition of bicarbonate to carbonate ions (Eq. (2)). The carbon dioxide quickly decomposes in the presence of water into bicarbonate (HCO_3^-) and it reacts with the hydroxyl ions to form carbonate ions (Eqs. (3) and (4)). Hence, in the presence of calcium ions (Ca^{2+}), the calcite ($CaCO_3$) is precipitated (Eq. (5)) (Castanier et al., 1999; Burne and Chen, 2000). The overall process of urea hydrolysis and formation of calcium carbonate are presented in Eq. (6). Fig. 1 shows the details of urea hydrolysis reactions for the precipitation of calcium carbonate by *Sporosarcina pasteurii*.

$$CO(NH_2)_2 + H_2O \rightarrow 2NH_3 + CO_2 \quad (1)$$

$$2NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH^- \quad (2)$$

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+ \quad (3)$$

$$HCO_3^- + H^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2H_2O \quad (4)$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\downarrow \quad (5)$$

$$CO(NH_2)_2 + 2H_2O + Ca^{2+} \rightarrow 2NH_4^+ + CaCO_3\downarrow \quad (6)$$

Environmental factors such as temperature and humidity affect metabolic reactions inside the cells and some physical properties such as viscosity and diffusion. Other factors such as availability of other microorganisms may restrict the available space for bacterial growth and activity, and limit the population of the bacteria. The soil pH value which generally increases the salinity of an environment affects adsorption, surface charge and dissolution of some minerals in the soil (Degens and Harris, 1997). Though microbes are viable to move freely within the voids of the soil aggregates, their movements are restricted by the narrow pore sizes formed by fine-grained soils. Bacteria sizes range between 0.5 μm and 3 μm, as such they are not likely to pass through pore spaces smaller than 0.4 μm. Likewise, fungi and protozoa require pore sizes greater than 6 μm to pass (Castanier et al., 2000). Fig. 2 shows comparison of soil particle sizes and microorganisms. Meanwhile, in coarse-grained soils, bacteria can freely move between the soil mineral particles and may stick on the mineral surfaces and form microcolonies or biofilms.

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