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Physical and mechanical properties of reconstructed bio-cemented sand

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Abstract

The application of bio-treatment techniques to soil improvement has received attention in recent years in terms of quantifying gains in strength and stiffness while considering the environmental impacts. This paper presents the development of a system for a bacterial bio-cementation process in reconstructed samples. Then, the changes in the properties of cemented sands are examined through a set of physical, chemical, and direct shear tests. The bio-cemented sands resulted in higher shear strength due to the presence of cementation bonds leading to increases in cohesion and the friction angle. Furthermore, the effects of both the mechanical disturbance and the temperature-induced disturbance on the strength characteristics of cemented soils were investigated. The sheared specimens that were reconstructed by repeating the cementation process regained their shear strength. In addition, freeze-thaw cycles induced small amounts of disturbance and strength loss to the specimens where the highest disturbance occurred after the first cycle and during the largest temperature gradient.

Keywords: Biological cementation; *Bacillus pasteurii*; Freeze-thaw; Shear strength

1. Introduction

Engineers are commonly asked to build foundations on problematic soils; this often requires soil improvement. Thus, the application of soil-improvement techniques has played a crucial role in construction processes. Traditional soil-improvement methods have been based on cement injection or external soil stabilization procedures (Avramidis and Sexena, 1985; Zebovitz et al., 1989; Mitchell, 1981). Only recently, and due to environmental concerns, has the application of the bio-treatments of soils become attractive to engineers. Through such applications, higher strength and stiffness have been gained and environmental regulations have been met (Chahal et al., 2011; DeJong et al., 2010; De Muynck et al., 2010; Okwadha and Li, 2010; Whiffin, 2004; Stocks-Fischer et al., 1999). These innovative techniques were developed over the past two decades owing to the close collaboration among Civil, Environmental, Chemical, and Bio-Engineering specialists.

In general, there are two methods for the bio-mediation of sandy soils, i.e., bio-stimulation and bio-augmentation. In the bio-stimulation process, nutritious material is added to the soil to activate the bacterial growth as a result of the cultivation process inside the soil medium. Due to the difficulties of creating an appropriate environment for the bacterial growth in the soil, this method has been applied more to polluted soil clean-ups and less to the mechanical

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improvement of soils (Muyncka, 2010; Whiffin, 2004; Stocks-Fischer et al., 1999). On the other hand, in bioaugmentation methods, cultivated bacteria are added to the soil where both growth and cultivation stages are processed in the laboratory using a special fermenter. However, follow-up nutrients must be provided in order for the bacteria to survive. In addition, the required material for the chemical reaction of urea and calcium chloride should be supplied to the soil, so that the calcium carbonate can be deposited and create bonds between the particles. Calcium carbonate has been in existence in practice as a byproduct of microbiological processes such as photosynthesis and urea hydrolysis. The bacteria that have been used for calcium carbonate precipitation, which can be sedimented, are divided into two categories (Harkes et al., 2010): (1) Bascillus family: Aerobic bacteria that play the role of a catalyst in the urea hydrolysis process and produce calcium carbonate. (2) Nitrogen generators: Anaerobic bacteria that release nitrogen because of the reaction in the soil. The first method was implemented in this study and will be explained in further detail.

Microbial-Induced Carbonate Precipitation (MICP) has been the most progressive bio-cementation technique (De Muynck et al., 2010; Chahal et al., 2011; Whiffin, 2004; Okwadha and Li, 2010; Muyncka, 2010; Harkes et al., 2010; Achal et al., 2010; Sharma and Fahey, 2003; Whiffin et al., 2007). The general chemical reaction associated with this process is shown in Eq. (1).

$$CO(NH_2)_2 + CaCl_2 \rightarrow 2NH_4Cl + CaCO_3 \quad (1)$$

Recent works on the application of a specific type of bacteria, called "Bacillus Pasteuri", for introducing calcium carbonate into sands, has shown promising results (e.g., Chunxiang et al., 2009). A few studies have investigated the effects of this technique on the engineering properties of soils and the consequent changes in the mechanical characteristics (DeJong et al., 2010; Muyncka, 2010; Harkes et al., 2010; Sharma and Fahey, 2003; Whiffin et al., 2007; Lin et al., 2016). DeJong et al. (2010) summarized the biological processes in the soil and the possible subsequent effects on the engineering properties. These include experimental research on the effectiveness of the bacterial system, the bio-chemical processes in the production and progression of the bacteria and its retention inside the soil, a comparison of the mechanical properties before and after precipitation, and the compatibility with the environment. Although several studies have reviewed the bio-cementation processes with a focus on the chemical and biological interaction of bacteria and soil minerals (Achal et al., 2010; Stocks-Fischer et al., 1999; Whiffin, 2004; Al Qabany and Soga, 2013), the mechanics of bio-mediated soil is in its early stages of research. Some recent studies include the real-time monitoring of the shear wave velocity to understand the cementation process in MICP (Lin et al., 2016), direct shear tests to measure the shear strength of cemented organic soils (Canakci et al., 2015), triaxial tests to capture the stress-strain response of cemented sand under different loading paths (Montoya and DeJong, 2015; Feng and Montoya, 2015; O'Donnell and Kavazanjian, 2015; Lin et al., 2016), the large-scale application of MICP for soil improvement (Gomez et al., 2016), and physical model tests to investigate the influence of MICP on the response of soil systems, such as piles or liquefaction mitigation (Lin et al., 2015). One key aspect of the response of bio-cemented soils is their recovery after disturbance, which was discussed through the healing effects of biologically cemented material (Montoya and DeJong, 2013). This phenomenon requires further investigation when the cemented soil has undergone various types of disturbance.

In this paper, the process for preparing bio-cemented sandy specimens using the calcium carbonate precipitation technique is discussed and the experimental procedure is explained. The physical, hydraulic, and mechanical characteristics of the sand before and after cementation were monitored. Also, a set of direct shear tests was performed on both clean and cemented sands, and the frictional and cohesion resistance characteristics were compared. Mechanical and temperature-originated disturbance was introduced to the cemented specimens, and the strength properties of the reconstructed specimens were investigated. Specifically, the sheared specimens were reconstructed by repeating the calcium carbonate precipitation procedure. In addition, cycles of freeze-thaw were imposed and variations in strength of the cemented specimens were examined.

2. Cementation procedures

2.1. Material

A poorly graded clean silica sand was selected for this study with the grain size distribution shown in Fig. 1 and the physical properties presented in Table 1. This sand has particle sizes mainly in the range of 250–300 μm and has been shown to be suitable for the cementation process (Achal et al., 2010). The soil specimens were prepared with a unit weight of 17.9 kN/m^3, corresponding to a void ratio of 0.73 and a gravimetric water content of 20.5%. This density resulted in an internal friction angle of 36° and negligible cohesion.

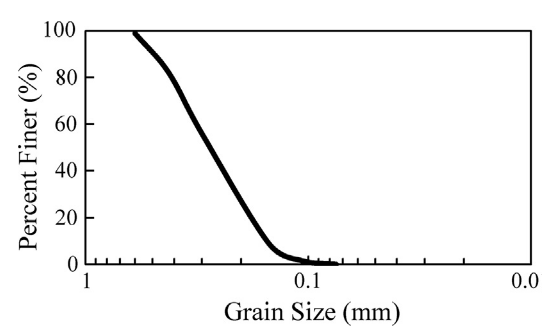

Fig. 1. Grain size distribution of tested sand.

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