Ecological Engineering 89 (2016) 49–55

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Effect of injected bacterial suspension volume and relative density on carbonate precipitation resulting from microbial treatment

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ARTICLE INFO

Article history:
Received 19 June 2015
Received in revised form
20 December 2015
Accepted 22 January 2016
Available online 4 February 2016

Keywords:
Microbial-induced calcite precipitation
Bio-grout
Biological improvement
Relative density

ABSTRACT

Microbial-induced calcite precipitation (MICP) is a relatively green and sustainable soil improvement technique in which by-products of a chemical reaction network managed and controlled by biological activity alter the engineering properties of the soil. The present study carried out a range of laboratory tests to investigate the effect of reducing the injected volume of bacterial suspension and the relative density (as a soil parameter) on bacterial retention, calcite precipitation, and improvement in the strength and impermeability of sand specimens. The results show that reducing the volume of injected voids to up to one third of the pore volume did not significantly affect the improvement performance. This is important as it can improve the efficiency of the process and make it economical and more practical for engineering applications. For similar microbial-induced calcite precipitation conditions and soil type, the final strength of the improved columns increased and permeability decreased as the relative density of the soil increased slightly as precipitated calcite decreased.

1. Introduction

Rehabilitation and expansion of civil infrastructures is required to meet ever-growing societal needs, but is directly limited by the availability of competent soil upon which they can be constructed (DeJong et al., 2010). Some products used for treatment of soil are not considered as environmentally friendly because of pollution and toxins produced during manufacturing and application (Gurbuz et al., 2011). Among the range of treatment techniques, microbial-induced calcite precipitation (MICP) is a relatively green and sustainable soil improvement technique (Ng et al., 2012). It refers to a chemical reaction network that is managed and controlled within the soil through biological activity that produces by-products that alter the engineering properties of the soil (DeJong et al., 2010).

MICP has been used to mitigate engineering problems, such as for crack repair in concrete (Ramachandran et al., 2001; Nelson and Launt, 1991; De Belie and De Muynck, 2009), to reduce permeability (Nemati and Voordouw, 2003), for repair of calcareous monuments (Dick et al., 2006; Jimenez-Lopez et al., 2008), to improve compressive strength of concrete (Ramachandran et al., 2001; Jonkers et al., 2010), to improve concrete durability (De Muynck et al., 2008; Achal et al., 2011), for selective plugging at enhanced oil recovery sites (Gollapudi et al., 1995; Nemati et al., 2005), for wastewater treatment (Hammes et al., 2003), to improve soil (Whiffin et al., 2007; Ivanov and Chu, 2008; DeJong et al., 2010), to increase durability of bricks (Sarda et al., 2009) and as bio-concrete (D'Aquino Henriques, 2011). MICP has the potential of increasing shear stiffness and decreasing hydraulic conductivity by harnessing a natural microbiological process that precipitates calcium carbonate (Martinez et al., 2013).

Microbial urease hydrolyses urea to produce dissolved ammonium and inorganic carbon, and CO_2. The ammonia released into the surrounding material increases pH, leading to accumulation of insoluble $CaCO_3$ in a calcium rich environment. Quantitatively, 1 mol of urea hydrolyses intracellularly to 2 mol of ammonium (Eqs. (1) and (2))

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

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

These reactions occur under the influence of natural environmental factors that control the activity of the urease. Subsurface bacterial populations can be put in place by injection (DeJong et al., 2006) or stimulated by injection of nutrient materials (Fujita

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http://dx.doi.org/10.1016/j.ecoleng.2016.01.010
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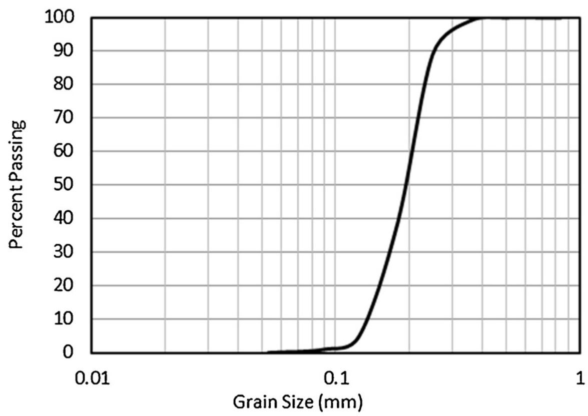

Fig. 1. Grain size distribution of material.

et al., 2008). In the present study, augmentation was carried out in columns with one-dimensional flow.

Reagents and catalysts must be injected and transported to the location at which strengthening is required to induce MICP in subsurface soil. The two-phase injection method for bacterial retainment suggested by Whiffin et al. (2007) was used in the current study. This process for homogeneous immobilization of bacteria first injects the bacterial suspension and then injects a fixation fluid (a solution with high salinity). This approach has been frequently used (e.g., Harkes et al., 2010; Whiffin et al., 2007; Kaltenbacher et al., 2014; Martinez et al., 2013; van Wijngaarden et al., 2012; Sarmast et al., 2014; van Paassen et al., 2010).

The use of a high injection volume is not desirable for grouting. A disadvantage of this approach is the injection of 2 pore volumes (PV) before injection of the main cementation liquid (Harkes et al., 2010). The volume of injection is not very important for laboratory research; thus, many laboratory studies use high-volume injection. In most cases, 1 PV or more of bacterial suspension is injected and a high volume of cementatious material (up to 30-fold) is flushed (Harkes et al., 2010; Whiffin et al., 2007; Shirakawa et al., 2011; Tagliaferri et al., 2011; Tsukamoto et al., 2013; Mortensen et al., 2011; Ng et al., 2012). For improvement of larger bodies, there are restrictions that decrease the volume of bacterial suspension injected. For example, van Paassen et al. (2010) injected 100 L of bacterial suspension for a m^3 specimen; for a 100 m^3 specimen in which 40 m^3 was improved, a mere 5 m^3 of bacterial suspension was injected.

Although many studies exist on relative density (RD), these studies do not cover the entire improvement process. Different aspects of the effect of RD on improvement have been evaluated. Cheng et al. (2014) compared the strength of improved loose and dense samples in terms of their calcite content and concluded that at the same calcite content, the looser sample showed less strength. Chou (2007) studied loose and dense microbially-improved sample behaviour in California bearing ratio (CBR) and shear tests. They found that improving the friction angle improved the strength more in loose samples in shear tests but that dense samples recorded more strength enhance in CBR tests.

Tsukamoto et al. (2013) used sand samples with RDs of 30%, 65% and 85% to study improvement in parameters during three axial tests. They showed that more calcite precipitated at lower RDs, but that strength decreased. Kim et al. (2014) studied the effect of RD after mixing bacteria and soil without injection. They found that maximum carbonate precipitation in sand occurred at a RD of 60% and in silt at 90% compaction. Ng et al. (2012) tested residual soils having 85%, 90% and 95% compaction by mixing them with bacteria and injection of cementation fluid. They found that shear strength increased, but permeability decreased, as relative density increased.

It is evident that none of the numerous studies in the literature consider the effect of relative density in a complete process. Scatter can be observed in the results as an effect of soil properties or improvement conditions. The present study evaluated the effect of relative density after complete injection and improvement on bacterial fixation, calcite precipitation, strength, and permeability. The effect of decreased bacterial suspension at different relative densities is investigated.

2. Materials and methods

The present study investigated the effect of improvement of soil at different RD using void injection experiments on soil samples in a 20-cm column.

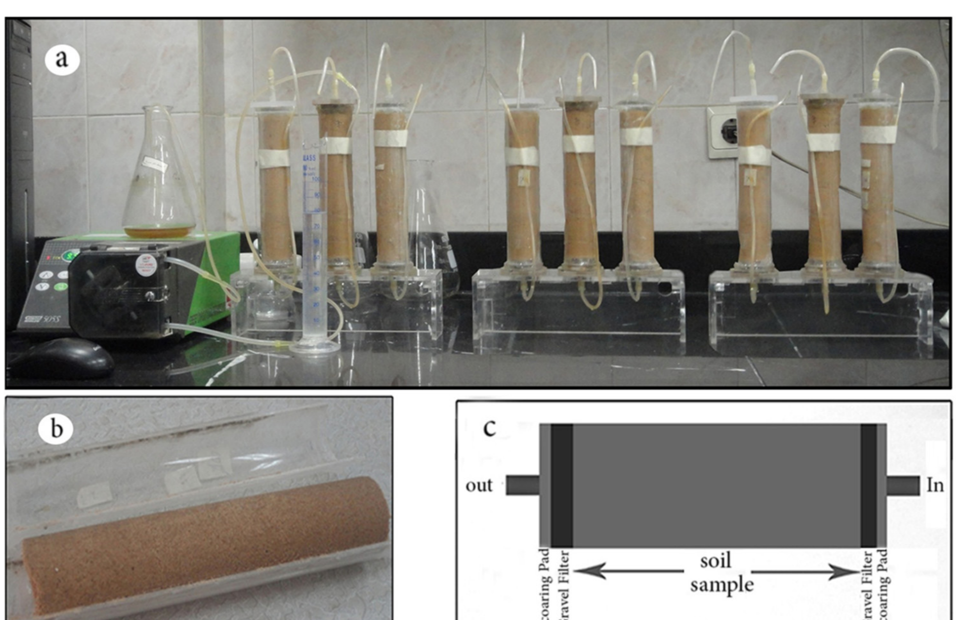

Fig. 2. Columns: (a) during treatment; (b) improved; (c) setup schematic.