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Bio-stabilization of Sand by Surface Percolation

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ABSTRACT: Most traditional soil improvement methods are time consuming, expensive, require heavy machinery and are environmentally detrimental. As a more environmentally favorable ground improvement method, the bio-cementation of soil offers an alternative to traditional soil improvement techniques. This method is based on microbial precipitation of calcium carbonate. The role of bacteria is producing urease enzyme to catalyzing the hydrolysis of urea. In the presence of calcium ions, the produced carbonate ions in hydrolysis of urea react with the calcium ions and calcium carbonate sediment is formed. This paper investigates the applicability of the bio-remediation of dry loose sand by surface percolation. To evaluate the success of treatment, a series of laboratory experiments was conducted, including, shear wave velocity, unconfined compressive strength, Brazilian tensile strength, calcium carbonate content and etc. The study revealed that the bio-remediation technique causes the improvement of soil strength as a result of the cementation of sand particles. Furthermore, the surface percolation method has the potential of cementation and stabilization of loose sand with desirable depth. Increase in soil strength and calcium carbonate content decreases with increase of depth. Results also showed that increase of strength due to bio-improvement depends to calcium carbonate content, its spatial distribution in pores and particle-to-particle binding numbers.

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1- Introduction

Due to overpopulation in urban areas, and an increasing shortage of ideal construction sites, there has been an increased need for the development of new techniques to improve the mechanical properties of natural soil.

Current soil improvement techniques are time consuming, expensive and in the case of chemical grouts are environmentally toxic and/or hazardous [1-3]. Recently, the bio-mediated ground improvement by Microbial Induced Carbonate Precipitation (MICP) method has experienced an increased level of interest by microbiologists and engineers and its efficiency has also been proved by some researchers at small and large scales in laboratory and field experiments [4-6].

In this technique an aerobically cultivated urease-producing bacteria introduces into soil to catalyze the hydrolysis of urea to produce ammonium and carbonate ions through following chemical reaction:

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

In the presence of calcium ions, the calcium carbonate ($CaCO_3$) crystals precipitate based on the following chemical reaction which form cementing bonds between the existing sand grains [7]:

$$Bacteria\ Cell - Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3\left(s\right) \quad (2)$$

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Most investigations on the bio-mediated soil improvement has been limited to using water logged soils below groundwater [4, 8]. The cementation of dry sands above the groundwater table has not been studied and described extensively.

The aims of this paper are to investigate the possibility of bio-stabilization in unsaturated sands, efficiency of surface percolation method and changes of soil engineering and microscopic characteristics in the effect of this type of modification.

2- Materials used

2- 1- Soil

Firoozkooh No. 161 silica sand was used in experiments. According to the Unified Soil Classification System (USCS), this sand is graded as poor sand (SP) with uniform distribution. Figure 1 shows the results of the grain size distribution curve. The soil pores should be large enough to let the bacteria into the soil. Bacterial cells are typically 0.5–3.0 µm in diameter [9]. As shown in Figure 1, the range of particle size is favorable for bacterial activity in the pores so it is expected the bio-improvement occurs sufficiently in this soil.

2- 2- Micro-organism

Sporosarcina pasteurii (PTCC 1645) due to its high urease activity has been used in laboratory studies. A sterilized medium consisting of 10 g/l of ammonium chloride and 20 g/l of yeast extract at pH=9 was selected for bacterial growth. The growth medium was inoculated with the S. pasteurii seed culture and incubated aerobically at 30 °C in a shaking incubator (170 rpm) for approximately 24 h before harvesting at a final optical density (OD_{600}) of 1.0. The urease activity was approximately lower than 2 mMurea/min.

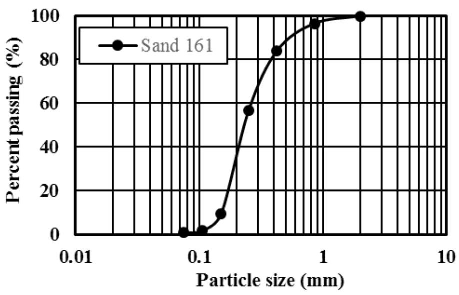

Figure 1. Grain size distribution curve of sand

2- 3- Cementation solution

Cementation solution consisted of 0.3 M $CaCl_2$ and 0.3 M urea.

3- Test setup and treatment procedure

Dry sand was air pluviated into each specimen mold to produce a loose sand state with relative density of 30%. The volume of the soil pore voids (Vv) was approximately 100 ml. solutions of volume Vv were introduced from the top of the specimens. The transport of liquids was the result of gravity with a flow rate of about 3 l/hr. The percolation method consisted of the following steps:

1. First day: Percolation of one pore volume bacterial suspension and allowing the fixation and attachment process to occur for 4-6 hr. After this retention time, each sand specimen was allowed to drain under gravity from its base. Next, percolation of cement solution (same amount as aforementioned bacterial suspension) and incubation for 24 hr, allowing the carbonate calcium producing bio-chemical reactions to occur. At the end of 24 h retention period, the each sand specimen was also allowed to drain under gravity from its base.
2. Next days: solutions equal to half pore volume replaced in step 1. This step repeated for Seven days.

After completing the MICP treatment, the drained specimens released from their split molds after 24 h.

4- Results

4- 1- Shear wave velocity

The shear wave velocity is calculated from the distance between the two Bender elements placed in triaxial cell top and bottom caps and the time required by the shear wave to cover this distance. The shear wave velocity of 46.73 m/s was obtained for untreated sand specimen. In the similar way, the shear wave velocity of 454.5 m/s was obtained for bio-cemented sand sample. From the results, the shear wave velocity was increased about 10-fold after the treatment process. According to the MICP cementation level guidelines proposed by Montoya, B. M. and DeJong, J. T. [10], this treated sand sample is lightly to moderately cemented sand.

4- 2- Unconfined compressive strength (UCS) tests

The average unconfined compressive strength (UCS) of cemented specimens with a selected height to diameter ratio of 1.3, 1.6 and 2 are 324.47, 81.54 and 18 kPa, respectively. It can be seen that the strength of the treated samples significantly decreases with the increase of height/diameter ratio. This was caused by inhomogeneous calcite distribution due to high bacterial activity near the surface and consequently crystal accumulation, more and strong bonds in the upper part of specimen. Excessive calcium carbonate formation and higher strength near the injection source have been reported by other researchers [5, 11]. The failure mechanism of the cemented sand also confirms the nonhomogeneous cementation over the length of specimen.

4- 3- Indirect tensile strength (Brazilian) tests

For stabilized materials, the Brazilian test is commonly used for measuring tensile strength. According to Figure 2, tensile strength and calcium carbonate content decrease over distance from the injection point. It can be seen that in lower parts of the samples, for similar produced $CaCO_3$ content, the samples have different tensile strength. It is apparent that it is not the amount of produced calcium carbonate content that governs the strength of treated soils but rather the spatial distribution of it and the amount of produced cementitious bonds between grains contact.

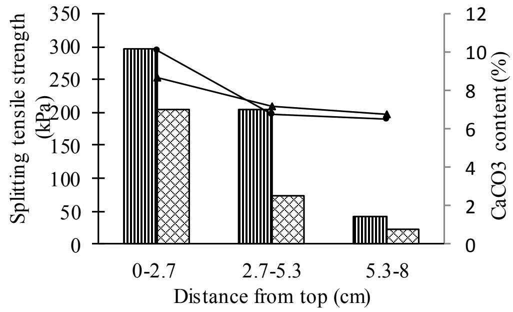

Figure 2. Tensile strength and $CaCO_3$ content over the distance from surface, (▲) and (●) are calcium carbonate content of the (▥) and (⊠) specimens respectively

4- 4- Microscopic image

To examine the arrangement of calcium carbonate crystals between the sand grains, a thin sliced section of the cemented sand was examined under microscope. As shown in Figure 3, most of calcium carbonate crystals coated the surface of the sand particles or precipitated in pore voids. This is why the cemented sand in this study shows lower strength compared with previous researches. For instance, Van Paassen et al. achieved an unconfined compressive strength of 12 MPa from samples of microbially-grouted sand [12].

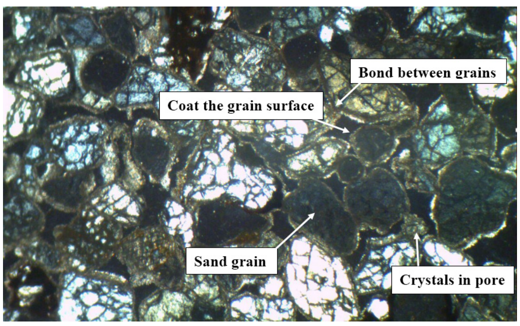

Figure 3. Thin section of the cemented sand

5- Conclusions

This study showed that bio-cementation of sand is feasible by surface percolation method. This technique could lead to a successful cementation without clogging the injection point. Laboratory tests on the bio-cemented sand showed that:

- Increase of shear wave velocity confirms the increase of average shear stiffness due to cementation occurred at particle to particle contacts.
- Tensile and compressive strength of bio-cemented samples increased, although this increment decreases over distance from the sample surface.
- High percentage of precipitated calcium carbonate proved to be an inadequate indicator to estimate the strength of bio-cemented soil. Other factors such as crystals precipitated and the strength of cementitious bonds between grains are also effective.

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