Evaluation of Biogrouting Method in Sandy Soil improvement in Column Injection Experiments

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Abstract

Improvement of soils is among the major concerns in civil engineering. For this, a variety of approaches have been employed for different soil types. The annual budget of implementing the projects of this kind in countries clearly implies the importance of the subject. The loose granular soils and sediments have always imposed challenges due to their low strength and bearing capacity as well as difficulties in drilling and excavation. Biogrouting has recently been introduced as a novel link of biotechnology and civil engineering for improving the problematic soils, i.e. utilizing some bacteria to precipitate calcite on the soil particles. In the present study, the Sporosarcina pasteurii PTCC 1642 (DSM 33) was used as the bacterial agent to improve soil strength parameters in a two-phase injection approach. Bacterial injection to a sandy soil column was followed by nutrients injection containing $CaCl_2$ and urea and the soil columns were settled in the ambient temperature. Experiments were performed in triplicates and conducted for two types of sandy soils. The unconfined compressive strength of soil specimens was evaluated after 15 days of the last injection. The results show significant increase in the soil strength with values of 1.78 and 2.83 Kg/cm2 for the two investigated soil types according to *t* test.

Key words: Biogrouting, Soil improvement, Bacteria, Column injection, Sandy soil

1. Introduction

Population and civil infrastructure continue to expand at unprecedented rates. The demand for new, sustainable methods to improve soil continues to increase, with more than 40,000 soil improvement projects being performed per year at a total cost exceeding US$6billion/year worldwide (ASCE, 2006). Infrastructure demands are even more severe in some other countries, particularly in India and China. Infrastructure is insufficient in countries such as China, where 10 million people immigrate to major cities each year. Population growth is particularly acute for historic cities and regions where expansion is limited by geographical boundaries and inadequate soil conditions, such as Boston, New York, Los Angeles, Mumbai, Tokyo, and Istanbul, and the countries like Holland and Japan.

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There are several methods for improving the soil properties in civil engineering. The majority of these soil improvement techniques utilize mechanical energy and/or man-made materials, both of which required substantial energy for material production and/or installation (Cayan et al., 2008). A common approach is to inject synthetic man-made materials, such as micro-fine cement, epoxy, acrylamide, phenoplasts, silicates, and polyurethane into the pore space to bind soil particles together (Xanthakos et al., 1994; Karol, 2003). These approaches result in environmental concerns and are increasingly under the scrutiny of public policy and opinion as all chemical grouts except sodium silicate are toxic and/or hazardous (Karol, 2003). In 1974, acrylamide grout was associated with five cases of water poisoning in Japan, resulting in the ban of nearly all chemical grouts (Karol, 2003). This reverberated in the US, with pending federal regulations forcing the withdrawal of most products on the market. Recent initiatives in certain countries propose to ban all synthetic man-made grouting materials (DeJong et al., 2010).

An interdisciplinary method has recently been introduced as a novel link of biotechnology and civil engineering for improving the problematic soils. Biogeotechnology is a branch of Geotechnical Engineering dealing with the biological methods applications for geotechnical engineering challenges. A bio-mediated soil improvement system broadly refers to a chemical reaction network that is managed and controlled within soil through biological activity and whose byproducts alter the engineering properties of soil (DeJong et al., 2010). In such a soil improvement system, the bio-mediated chemical reaction network is regulated to control the timing of the reaction. This is enabled by the amendment of chemicals into the subsurface. The microbial population in-situ is typically either stimulated through the injection of nutrients or augmented by the injection of additional microbes, which are called bio-stimulation and bio-augmentation, respectively. In either case, the goal is to increase activity levels and/or concentrations of the microbial population to the level required to initiate and sustain a chemical reaction (DeJong et al., 2010).

The use of microbes to control and manage the chemical processes is attractive given their pervasive presence in the subsurface and the millennia over which they have been active. More than 10^9 cells per gram of soil exist in the top meter of soil and the population concentrations generally decrease with depth. At 30 m depth, the lower limit of most soil improvement engineering applications, microbe concentrations of about 10^6 cells per gram of soil can exist (Whitman et al., 1998).

Biogrout is a soil improvement system that is based on microbial induced carbonate precipitation or MICP. In this system, the biological process leading to precipitation of calcium carbonate is employed. There are many biological processes, which lead to precipitation of calcium carbonate (Castanier et al., 1999), but not all are suitable for ground reinforcement. For this purpose, some certain types of bacteria capable of converting urea into ammonium and carbonate ions are injected into the soil, and is followed by injecting a solution of urea and calcium chloride. The carbonate produced from the bacterial activity combines with calcium ions presented in the medium and precipitate calcium carbonate, i.e. calcite. The formula below shows the overall reaction that takes place in the soil:

$$CO(NH_2)_2 + CaCl_2 + 2H_2O \rightarrow 2NH_4Cl + CaCO_3 \text{ (solid)}$$

An advantage of microbial grouting over chemical one is that the microbial grouts may be non-toxic, whereas many chemical grouts, especially those based on acrylamides, lignosulfonates, and polyurethane, are toxic and environmentally harmful. Another advantage of microbial grouting over chemical one is the lower cost of reagents. The

evaluated costs of the raw materials for the chemical soil grouting are in the range from $2 to $72 per $1m^3$ of soil (Ivanov et al., 2008). The chemical grouts, especially those based on acrylates, acrylamides, and polyurethanes are most expensive. The costs of the raw materials for the microbial grouting could be in the range from $0.5 to $9.0 per $1m^3$ of soil in cases when the waste materials are used as the source of carbon for microbial growth (Ivanov et al., 2008).

Biogrouting has been applied for soil improvement in column injection investigations by several researchers. First study of biogrouting was carried out with a cylinder of 16 cm height (Whiffin, 2004). In 2007, Whiffin et al. have published their work on the scale up process of this method. They proved that cementation could be induced over a long distance from an injection point. A PVC column (66 mm in diameter and five meter in length) was placed vertically and injection was carried out (Whiffin et al., 2007). In 2008, Ivanove et al. evaluated the microbial applications to geotechnical engineering and using of MICP for in-situ soil improvement approaches (Ivanov et al., 2008). Van Paassen et al., in 2009, evaluated the effect of ionic strength on microbial transport and using fixation fluid to avoid remobilizing bacteria from soil column during injection (Van Paassen et al., 2009). In 2010, Van Paassen et al. evaluated the potential of BioGrout for field applications. Experiments were performed in controlled 3D environments, using conditions and injection techniques resembling those envisioned in practice two experiments were performed in a box with a volume of cubic meters and 100 cubic meters (Van Paassen et al., 2010). In 2011, Mortensen et al. evaluated the effects of environmental factors on microbial induced calcium carbonate precipitation. Soil column and batch tests were used to assess the effect of likely subsurface environmental factors on the MICP process. Microbial growth and mineral precipitation were evaluated in freshwater and seawater. Environmental conditions that may influence the ureolytic activity of the bacteria, such as ammonium concentration and oxygen availability, as well as the ureolytic activities of viable and lysed cells were assessed. Treatment formulation and injection rate, as well as soil particle characteristics are other factors that were evaluated for impact on uniform induction of cementation within the soils (Mortensen et al., 2011).

2. Data and Material

A) Chemicals and Soil:

Urea and CaCl2 used as nutrients were purchased from Razi Petrochemical Co. and Kimia Mavad Co., respectively.

Two soil types were prepared from Chirook Company located in Tabas area of central Iran.

B) Microorganism:

The bacterium Sporosarcina pasteurrii PTCC 1642 (DSM 33), purchased from Persian Type Culture Collection, was used in this research as an alkalophilic soil bacterium. According to the literature, the bacterium has a highly active urease enzyme (Ferris et al., 1996). The lyophilized microorganism was recovered in appropriate medium, cultivated on Trypticase Soy Agar (TSA) medium, and preserved in 4◦C before biomass production.

3. Research Methodology

A) Soil Properties:

Two types of sandy soil were utilized and were named S1 and S2 for facilitation. Particle size analysis of soils was carried out according to ASTM D422 – 63 (2007) and classification of soils was carried out according to ASTM D2487 - 11. Soils properties were shown in Table1.

Table 1: Characteristics of the investigated soil types

Soil Type	Sieve No.	Percent Passing	Soil Classification
S1	4	100	SP
	200	1.57	
S2	4	100	SP-SM
	200	9.5	

The particle-size distribution curves of the used soil types are presented in Fig1~2.

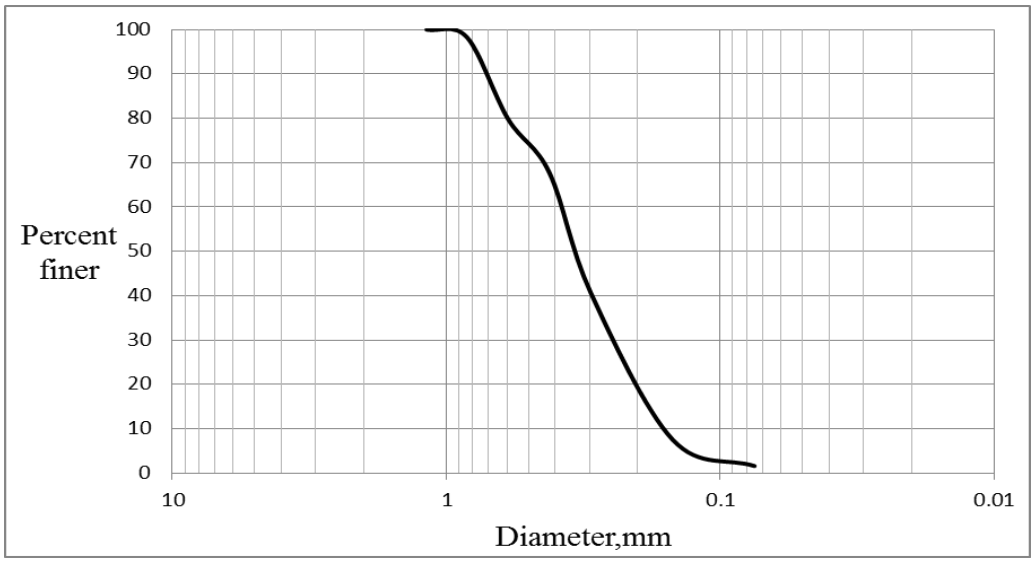

Fig 1: Distribution curve of S1

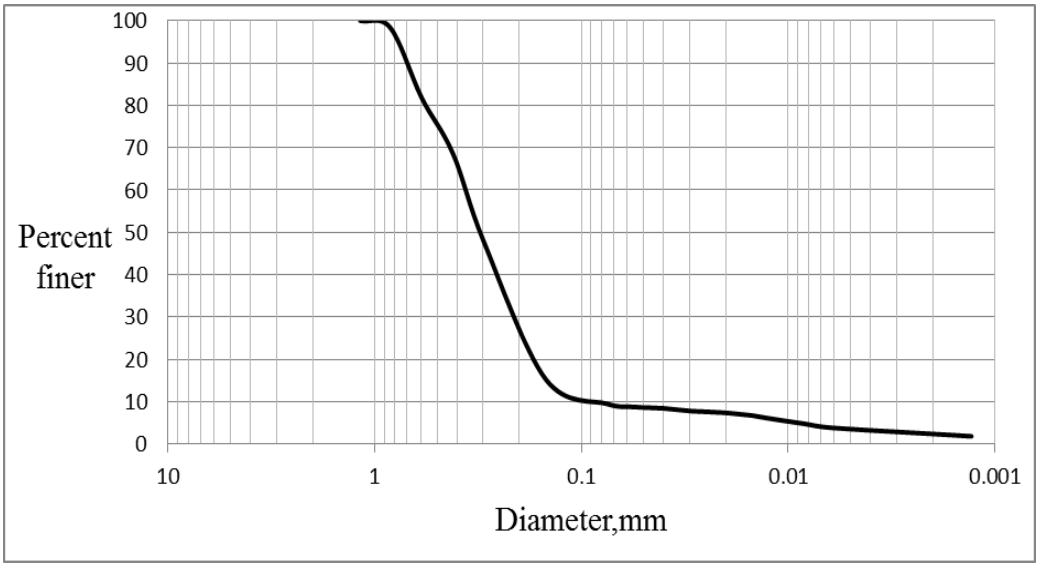

Fig 2: Distribution curve of S2

B) Biomass Preparation:

For preparing bacterial cells required for injection, the bacteria were aseptically transferred into a cultivation medium containing peptone (20 g/L) and NH_4Cl (10 g/L) with a pH adjusted to 8.5. The cultivation flasks were incubated under aerobic batch conditions for 24 hours in a shaker incubator with 30°C and under 170 rpm. After this incubation time, the optical density at 600 nm or OD_{600} of 4 was achieved for the medium. After 24 hours, reaching to the late exponential phase of the bacterial growth, the medium congaing bacterial cells was condensed by centrifuge for 10min. at 4000 rpm. Then, the biomass was separate and transferred to 9 g/L sodium chloride solution in order to prepare the desired concentration of the biomass suspension. For this, bacterial suspension optical density at wavelength of 600 nm was adjusted to 2.5. Finally, the resulted suspension of bacterial cells, i.e. biomass suspension, was stored at 4°C for 24 hours prior to use. The urease activity remained relatively stable over 25 days at 4°C according to the Whiffin, 2004.

C) Nutrient Solution:

In these tests, a solution of urea 3 M and $CaCl_2$ 1.5 M was used as the substrates for bacteria.

D) Injection Experiment:

The 17-centimeter-long PVC mold (internal diameter 40 mm) was positioned vertically and packed with soil. The column was positioned vertically with downward flow direction to avoid any settling of the packing material and generation of preferential flow paths that may occur if the column was positioned horizontally. Each end of the column was fitted with filter material consisting of a layer of scouring pad (Scotch) at the outside next to the sand. The scouring pads at each side were covered by a plastic cap. The prepared mold has been shown in Fig 3.

Fig 3: Prepared mold

For each soil type three experiments were performed and the average of the results was compared with the control specimens injected only with urea and calcium chloride.
For the injection experiments, the bacterial suspension prepared before was injected along with urea and calcium chloride to the soil columns. At first, specimens were injected by 110 ml of water for rinsing, and then 110 ml solution containing urea 3 M and $CaCl_2$ 1.5 M was injected, followed by 110 ml of bacterial suspension. After this step, the specimens were placed at ambient temperature to react for 24 hours. Then 110 ml of a solution containing urea 3 M and calcium chloride 1.5 M was injected. After 24 and 48 hours, the last injection was repeated. After 24 hours of the final injection, the specimens were carefully removed from the mold and stored at ambient temperature for 15 days for cementation process. Finally, the specimens were subjected to the unconfined compressive strength (USC) test to evaluate the injection effect on soil strength. Specimen was subjected to the unconfined compressive strength test in failure time was shown in Fig 4.

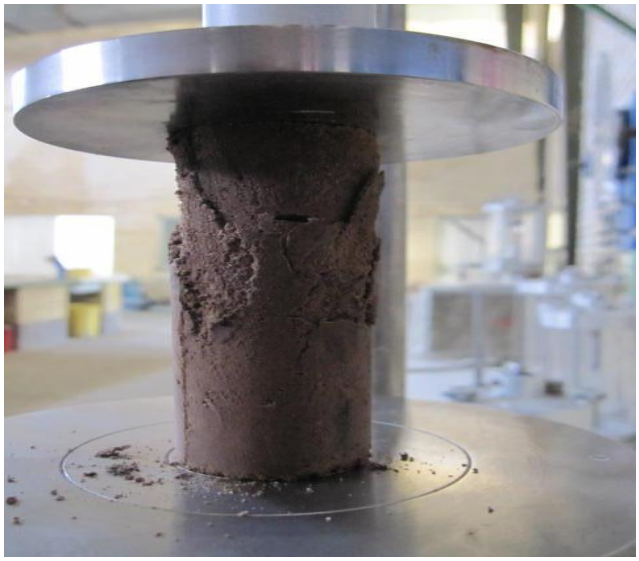

Fig 4: Specimen in failure time

4. Results and Analysis

All the tests were performed in triplicates and the arithmetic mean of the results were compared.
The resulted strength of the specimens was presented in Table 2. Also, the strength of the control specimens did not show any change in the USC test, and therefore, their strength were considered zero.

Table 2: Resulted strength of the specimens (Kg/cm^2)

Soil type	Rep1	Rep2	Rep3
S1	1.73	1.81	1.79
S2	2.82	2.87	2.80

The results were applied to *t* test and showed significant increase in the soil strength for each of the soil types comparing to blank specimens only injected with nutrient solution.

The bacterial injection performed in this investigation resulted in arithmetic mean of UCS values of 1.78±0.042 and 2.83±0.036 Kg/cm^2 for the two investigated soil types (Fig 5).

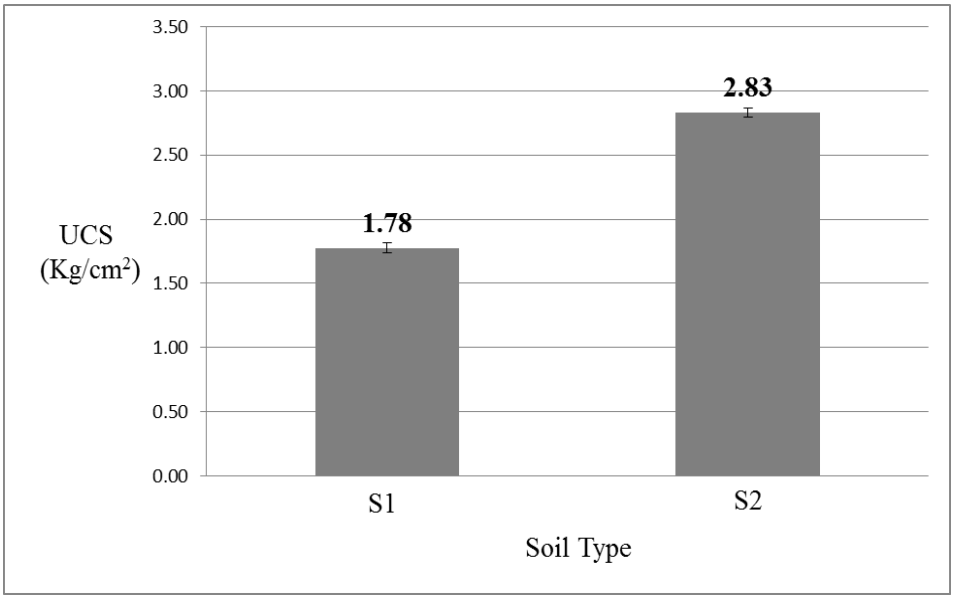

Fig 5: Resulted of USC for the two investigated soil types (average ± standard deviation)

The difference between the strengths of the investigated soil types is significant, according to *t* test. It seems that the difference could be due to the more fine grains passed through the sieve No. 200.

It should be noticed that the S1 is a soil with uniform particle size having very small clay percent which makes it one of the loosest sandy soil types for unconfined compressive strength tests. The obtained strength for the soil shows the efficiency of this technique for soil strength.

5. Conclusions

Application of MICP technique increased significantly the strength of the two soil types used in this research in the column injection experiments.

Microbial processes have central role in this approach as the injections lacking bacterial suspension and performed only using nutrient solution did not revealed any considerable strength for being estimated in USC test.

Soil type is a significant factor affecting the resulted increase in the soil strength, apparently due to the effect of particle size of each soil type. So, it is necessary to consider the local parameters including the soil characteristics and texture for any field and large scale applications of MICP technique.

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