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Improvement of Sand Soil with Bio-micropiles and Bio-grout Injection in Reinforced Soils

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ABSTRACT

The production of Portland cement, one of the most used materials in the construction industry, has increased environmental pollution and global warming. Soil bio-improvement is an eco-friendly and renewable method that has recently received attention. Microbially induced carbonate precipitation (MICP) has been the most researched for bio-geotechnical issues. *Sporosarcina pasteurii* is a micro-organism that produces urease enzymes and was used for sand soil improvement in this study. Also, the type of grout and injection method were selected as variables. The result of the test showed that the use of bio-grout had a significant effect on increasing the bearing capacity of soil. Bio-micropiles increased the bearing capacity by more than 94%. This increase was 126% in the case of cement-grouted micropile. Also, the results of the tests showed that the bearing capacity of bio-improved soil and reinforced soil increased by 54% and 125%, respectively. This research showed that bio-micropile could be a suitable method to replace cement-grouted micropile.

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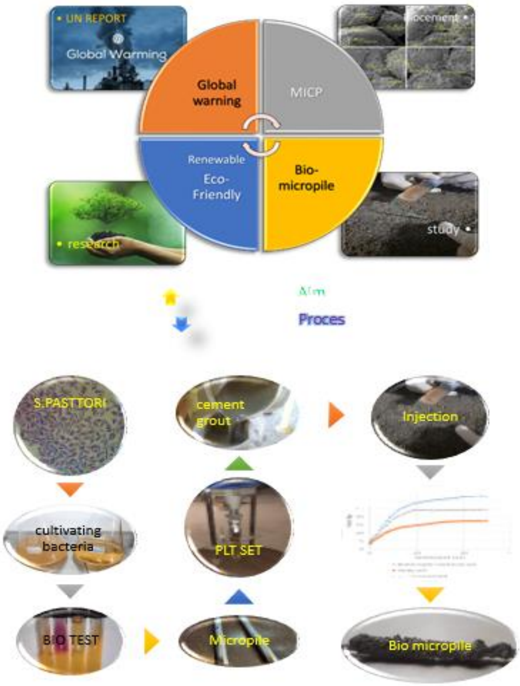
Graphical Abstract



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1. INTRODUCTION

The biological improvement of soils is a permanent, eco-friendly method that improves their mechanical properties (1). Soil Microorganisms have been active, renewable, anti-pathogenic, and eco-friendly on the earth for millions of years, but classical geotechnical engineering did not pay attention to this manner (2). The chemical reaction of urea hydrolysis is carried out so slowly in nature. Bacteria such as *Sporosarcina pasteurii* that produce urease enzymes increase the rate of urea hydrolysis up to 10^{14} times (3). Equations 1 and 2 showed calcium carbonate precipitation occurs on soil particles and bio-cementation. Finally, the soil's shear strength and stiffening increase. Also, its permeability and settlement decrease (Figure 1).

$$CO\ (NH_2)^2 + 2H_2O \rightarrow 2NH^{4+} + CO_3^{-2} \quad (1)$$

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

The potential applications for bio-cementation include soil strengthening for slope stability, liquefaction mitigation, seepage reduction, erosion prevention, and contaminant immobilization (4). Also, bio-grout is a bio-mineralization product that improves its mechanical properties. The bio-grout reaction is so slower than the chemical grout reaction. This solidification rate reduction allows the bio-grout to spread through soil species (5). Also, previous research showed that bio-grout helped to control soil permeability and bio-improve soil with bio-cementation (6). Bio-grout's other workability is wind erosion resistance. Bio-coating methods can control this problem (7). In addition, the generation of bio-denitrification from bio-grout injection and microbial metabolic activity affects the bulk modulus of the pore fluid. It thus reduces the generation of excess pore water pressure during shearing. Furthermore, microorganisms can form bio-film and bio-polymers by bio-grout injection, which may clog the pore space, reducing the permeability of the soil (8).

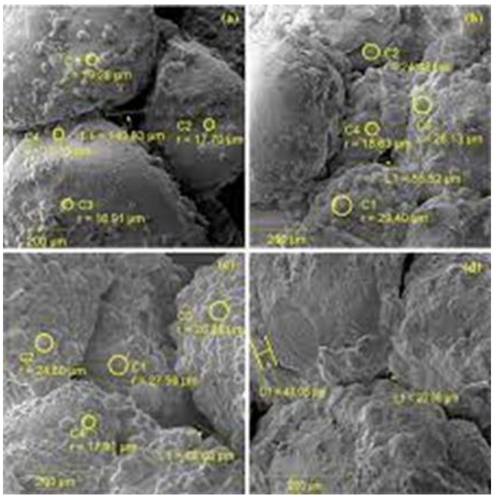

Figure 1. Microbially induced calcium carbonate precipitation (MICP) in sand particles

Moreover, soil reinforcing with micropiles, as a soil improvement method, has been used significantly since their conception in the 1950s (9). Micropiles used as foundations support elements to resist static and seismic load to a lesser extent, as in-situ reinforcements to soil improvement or provide stabilization of slopes and excavations of soil (10). Grouting operations have an impact on micropile bearing capacity (Figure 2).

Injected grout increases the bearing capacity of the micropile while protecting it from corrosion (11). The grout usually comprises a neat cement mix W/C ratio of 0.45. Cement production, as one of the most consumed construction materials, requires high energy and creates high pollution. Air emissions such as oxides of carbon dioxide, NOx, sulfur dioxide, polychlorinated dibenzo-p-dioxins, dibenzofurans, and their compounds increase environmental problems (10). The effect of bio-grout injection in micropile compared to cement-grouted micropile in this research is studied.

2. MATERIALS AND METHODOLOGY

2. 1. Sandy Soil Properties The tested soils of this research were the Mashhad Kashafroud River sand. The particle size distribution curve is shown in Figure 3; which is classified as poorly graded sand (SP) at the Unified Soil (USCS). Research showed that SP soil bio-precipitation amount is five times more than that of graded sandy soil (SW) with the same moisture and density (12).

The test soil had a specific gravity (G_s) of 2.65, a mean particle size (D_{50}) of 0.8 mm, and a maximum and minimum void ratio (E_{max} and E_{min}) of 0.90 and 0.57, respectively. The soil was non-cohesive, its cohesion was

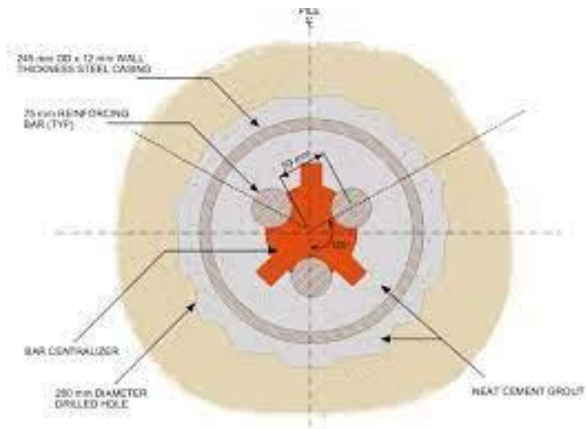

Figure 2. Grout-injected micropile general section

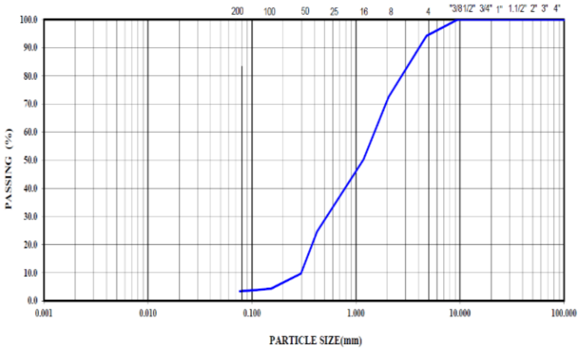

Figure 3. Kashafroud sand gradation graph

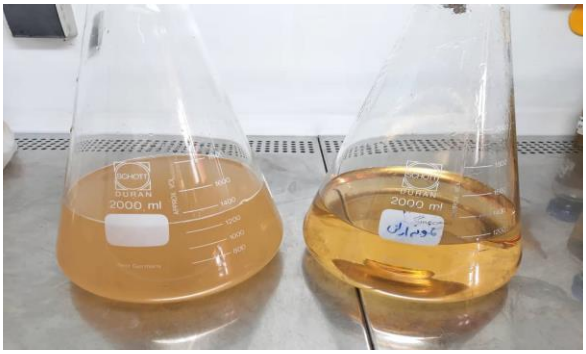

Figure 5. Bacterial cultures medium

zero, and its internal friction angle was 30° in the speed direct shear test (Figure 4). Also, soil pH is effective as a chemical characteristic in soil bio-precipitation. The research showed that MICP in an alkaline soil mass, with a pH between 7.5 and 9.5, had better function. The sample soil pH was 8.5.

2. 2. Bacteria Cultivation and Growth Condition

The most crucial parameter in microorganism choice for the MICP process is its ability to produce urease enzymes. Enzymes, as a bio-catalyst, significantly reduces the time of bio-precipitation. Research showed that the *Sporosarcina pasteurii* has the highest performance in urease enzyme production. Therefore, these microorganisms are used in the tests.

Bacterial cultures grew in an ATCC-specified medium. These bacteria are added to a Nutrient Agar culture medium containing 2% urea. First, 20 g of urea was dissolved in a liter poor water and about 8 g of nutrient broth culture, along with 100 mg of calcium chloride, was poured into Erlen and stirred well by a shaker (13). The liquid cultures were placed on a hot plate to have a solid culture medium. Then, nutrient agar was added to the solution (Figure 5). So, solid and liquid culture areas were prepared for the activation and cultivation of bacteria (14).

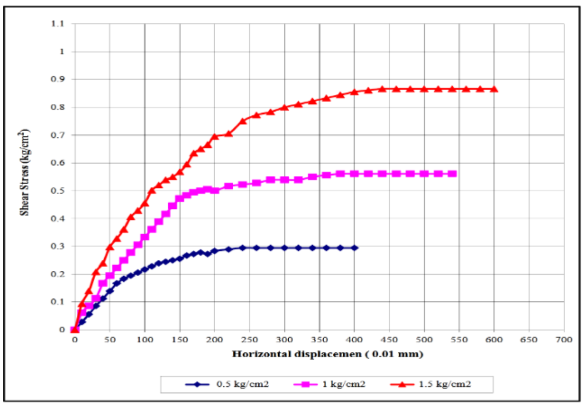

Figure 4. The result of Samples direct shear test graph

The calcium chloride and urea reagents are needed to complete the reaction and precipitation of calcium carbonate. This cementing solution increases the process of bio-precipitation like a catalyst.

2. 3. PLT Set and Parameters

Plate loading tests set are used to determine the ultimate bearing capacity and the probable soil settlement. The FHWA recommends that the thickness of the loading plate be more than ten times the maximum soil particles. Therefore, in research, the rigid steel loading plate with dimensions of 8*8*2 cm^3. Also, According to The Boussinesq approximation, for the distribution of stress bubbles under the loading plate to ignore the boundary condition, the diameter and height of the tank were 55 and 60 cm. The sand soil was compacted to prepare the specimens in three 15 cm layers with a moisture content of about 6% (Figure 6).

2. 4. Micropile and its variable parameters

The reinforced soil with four types of bio-micropile, cement-grouted, non-grout micropile, and reinforced soil with bio-grout injection, was tested in this research, and the steel core of micropiles were ST37 thin-walled steel tubes. Also, according to FHWA's recommendation, the

Figure 6. Plate loading tests set

micropile diameter was 0.8 mm, and its length was 200 mm. For better infiltration of the grout in the soil around the micropile wall and the formation of the grout sheath, the micropile was drilled in two perpendicular directions and at 4 cm intervals (Figure 7).

Cement grout prepared with FHWA recommendation. In this instruction, the executive classification of micropiles with gravity injection of grout with W/C 0.4 to 0.5 is placed in executive group A (15). Cement grout prepared with 20% micro-silica and 1% super plasticizer. Micro-silica, like other amorphous pozzolans, increases the mechanical properties of grout. The compressive strength and grout shrinkage amount in the first 2 hours tested. The results were 20.1, 28.6, and 31.2 MPa in 2, 7, and 28 days.

2. 5. Qualitative Test of Urease Enzyme Production Capacity The urease enzyme production capacity qualitative test is done in a solid culture medium. Due to the decomposition of urea and conversion to ammonia, the pH increases, and within 24 hours, the color of the cultivated area changes from yellow to pink (16). So, the culture areas are used for the isolation of urease-producing microorganisms. One liter of UAB culture area needs 20 g urea, 5 g sodium chloride, 1 g peptone, 1 g glucose, 2 g mono potassium phosphate, 12 mg red phenol, and 15 g agar. So, except urea, all of the materials were mixed in a laminar hood and placed in an autoclave (Figure 8).

After autoclaving, it cooled to a temperature of 38°C, dissolved urea was added to the area through a sterile filter, and then kept in an incubator at 25 to 30°C for 24 hours. During this period, the development of pink color was recorded in the culture medium.

2. 6. The Solution Concentration Control Continuous dilution method used for determining the

Figure 7. Non-grouted micropiles used in the tests

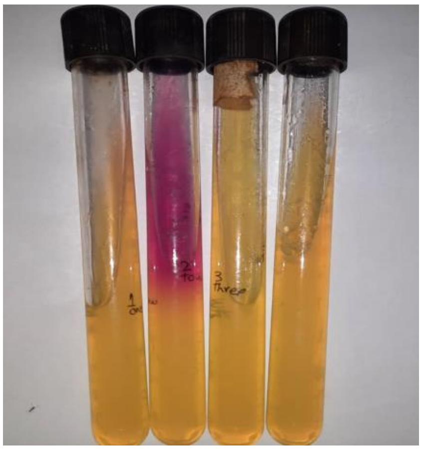

Figure 8. Qualitative test of urease enzyme production capacity

bacterium. First, 6 test tubes containing 9 ml of distilled water or sterile normal saline were placed consecutively, and 1 ml of the solution of the first test tube was transferred from the container containing cultured bacteria. The concentration of bacteria in the first tube is 10^{-1} of the source solution. This process continued until, at the last one, the solution concentration reached 10^{-6} of the main one. Then, 1 ml of solution was transferred into Petri dishes containing solid culture bacteria medium (17).

These were placed inside the incubator for 24 hours. After that period, bacterial cells are seen as colonies inside the culture medium. Then, the contents of each test tube are poured into the cells of the spectrophotometer that shows a number OD in the ABS part of the device by passing light and determining a specific wavelength. In this research, at the wavelength of 650 nm, the bio-grout OD was between 0.8 and 1.0.

2. 7. Reinforced Specimen Preparation and Grout Injection Process Research target was based on investigating the behavior of micropile-reinforced sand. In this part, the grout was injected at a slow and constant gravity injection rate inside the micropile. To drain the excess grout in this test, install a drain valve at the bottom of the tank. One-stage cement grout and two-stage bio-grout were injected into the micropile. Observations of the tests showed that micropile grout cover is dependent on the viscosity and type of grout. The amount of penetration of cement grout around the micropile was 15 mm. In bio-grout injection, Due to its fluid movement, was about 24 mm (Figure 9). In the other part, we studied bio-improved reinforced soil. In this research, bio-grout was injected in two stages. First, bio-grout was injected inside the micropile. So, it penetrated soil particles around the micropile. After 6 hours, we drained the soil by closing the drainage valve. After 2 hours of draining to bio-mineralization, calcium chloride is added to the soil. So, bio-cementation happened. The second step duplicates the first one. The tests showed that the grout penetration in the soil decreased by 35% in the second step injection. Previous research showed that, by increasing the six stages of injections, the penetration rate decreased by 75% (18).

2. 8. Reinforced and Bio-improved Soil Equalization Method The injection of bio-grout in soil with or without micropile changes the physical and mechanical characteristics of the soil. Micropile and bio-grout injection create a composite cross-section by increasing the soil stiffness and strength. The bio-grout injection also improves its conditions in interaction with micropiles and soil. There are various methods to check composite sections as bio-improved reinforced soil. The Transformed-Section Method is one of the most used methods to explain this situation. This theory is one of the methods used for bending stress analysis in composite sections (19).

This method is based on general relationships for linear or non-linear elastic materials. In this method, the cross-sectional area of the composite element with different stiffness is converted into the cross-sectional area consisting of a hypothetical equivalent material. This new cross-section is called a transformed cross-section (20). In this method use the dimensionless parameters. The equivalent stiffness and mechanical properties are shown in Equations 3 to 5.

$$\frac{A_{soil}}{a\times b} = \alpha \ \& \ \frac{A_{biocement}}{a\times b} = \beta \ \& \ \frac{A_{steel}}{a\times b} = \gamma \quad (3)$$

$$E_q = E_{soil}\left(\frac{A_{soil}}{a\times b}\right) + E_{biocement}\left(\frac{A_{biocement}}{a\times b}\right) + E_{steel}\left(\frac{A_{steel}}{a\times b}\right) \quad (4)$$

$$E_q = E_{soil} \times \alpha + E_{biocement} \times \beta + E_{steel} \times \gamma \quad (5)$$

Figure 9. Bio-grout injection in micropile

3. TEST RESULT ANALYSE

3. 1. Unreinforced Soil Test Results The results of the PLT test for unreinforced soil in Figure 10 showed that the unreinforced soil carried a 17.3 kg load at a 50 mm settlement. According to the plate dimensions, loose sandy soil, and without surcharge condition of the test, the bearing capacity was about 0.27 kg/cm^2. This amount was nearby according to experimental relationships such as Terzaghi's method, whose value showed a bearing capacity of about 0.26 kg/cm^2.

3. 2. Bio-improved Soil Test Results Results showed that bio-cement can be either solid or liquid. In liquid form, the bio-grout has a much lower viscosity and can flow like water. Thus, the delivery of bio-cement into soil is much easier compared with that of cement or chemicals. Furthermore, when using bio-cement, one usually must wait weeks for the stiffening, whereas when using bio-grout, the reaction time can be reduced if required.

The test results showed that the soil-bearing capacity increased with bio-improvement. The results showed that the bio-remedied soil had a growth rate of 54.1% with an increase in the final load equivalent to a 50 mm settlement compared to the sandy soil. The formation of connecting bridges and bio-calcite cementation between sand particles increased the bearing capacity (Figure 11).

3. 3. Reinforced Soil and Grouted-Micropile Result The injection of grout into the micropile and its penetration into the surrounding sand particles cements the soil and increases its mechanical properties by forming a composite section. In this research, cement-grout and bio-grout. The results of the tests showed that the non-grouted micropile increased the bearing capacity by 55%. The reinforced soil with micropile behaves as a composite specimen with higher characteristics than the

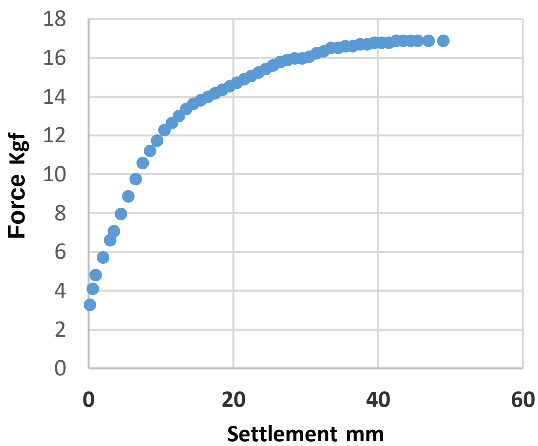

Figure 10. Unreinforced-soil PLT test result

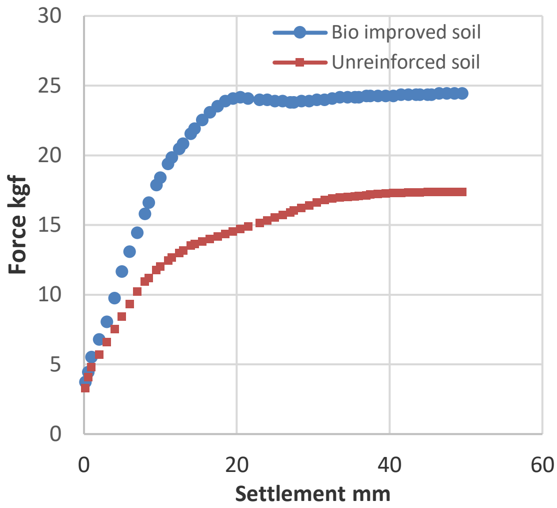

Figure 11. Bio-improved soil PLT test result

original soil. The cement grout injection inside the micropile created a suitable interlock between the grout, soil, and micropile. These increased the bearing capacity by 126%. While increasing the diameter and hardness of the micropile, the grout increased the frictional resistance between the sand particles and the rough surface of the micropile with cement grout.

Also, the results of the tests showed that the bio-grout injected into the bio-micropile penetrated the sand soil particles and increased the bearing capacity of the soil by 96% through bio-cementation. The comparison of these results showed that using bio-micropile can be a sustainable and Eco-friendly replacement for cement-grouted micropile. Soil reinforcement and the injection grout test results are shown (Figure 12).

3. 4. Bio-grout Injection Effect on Soil Reinforcement and Improvement The results showed that bio-micropiles increased the soil characteristics more than the bio-improving ones. The results showed that the bio-micropile case created a strong adhesion between the micropile wall and the bio-improved soil. Also, the injection of bio-grout in the micropile prevents the corrosion of the steel wall by creating a suitable cover with self-healing ability.

The research results showed that the bearing capacity in bio-micropile reinforced soil is 88.36% higher than in bio-improved soils. So, it has resulted in a transformed soil with a cross-section. Also, the test results in bio-improved soil showed that the bearing capacity of the soil increased by 40.55%. The selected method for soil improvement depends on the Problematic soil type and the required improvement amount (Figure 13).

3. 5. Bio-micropile Numbers Effect in Reinforced Soil Another influential parameter in increasing the bearing capacity of reinforced soil is the number and type of bio-micropile arrangement. In previous research, according to the dimension of micropile in soil reinforcement, the study is usually done on the micropile group. The number and arrangement of bio-micropiles in soil improvement are related to other parameters such as dimensioning, execution method, bio-micropiles distance from each other, and type of soil granulation. In this research, according to Figure 14, one, three, and five bio-micropiles were used under the arrangement shown.

The results of this research showed that, according to Figure 15, in the case of reinforcing soil with bio-micropiles with 8mm diameter and 14cm length, an increase in the bearing capacity of the soil compared to sand soil in the number of one, three and five bio-

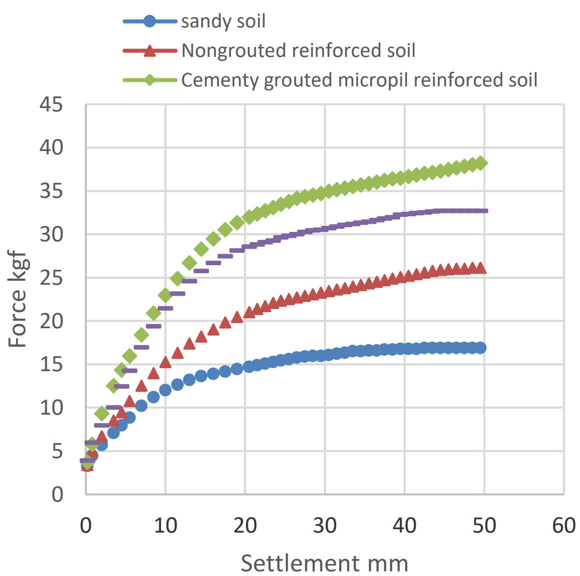

Figure 12. Reinfocing and grouting test result

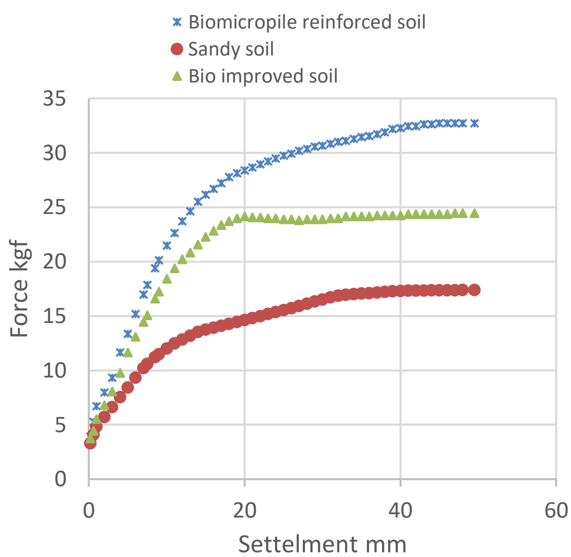

Figure 13. Reinforcing and bio-grouting test result

Figure 14. Five bio-micropile arrangment

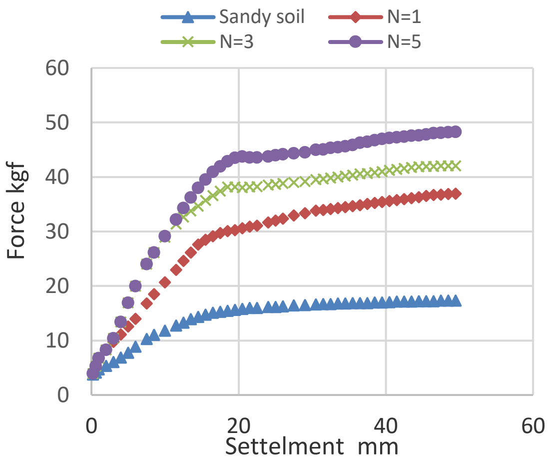

Figure 15. Five bio-micropiles arrangment results

micropiles because of stress distribution curves in the soil and the efficiency of the bio-micropile group are 113.4, 142.3 and 178.9%.

3. 6. Bio-improvement Reinforced-soil Test

This research studied the effect of bio-improvement on the soil-bearing capacity in reinforced and unreinforced soils. In the previous tests, bio-grout was injected into the micropile, and sand particles were cemented within a limited radius around the bio-micropile. In this test, all the soil is bio-improved by surface injection in two stages. The test results showed that bio-cemented soil has high stiffness and bearing capacity. The homogeneity of the residual resistance of this soil can be neglected due to the breaking of the bio-cement bond due to loading. In Figure 8, it was shown that an increase in the bearing capacity of the soil in unreinforced and reinforced bio-improved conditions was 41.1% and 127.6%, respectively. The improvement percentage of reinforced to unreinforced soil strength was 54.9% and 161.6%, respectively. Figure 16 illustrates the bio-improved reinforced soil test result. The coincidental integration of

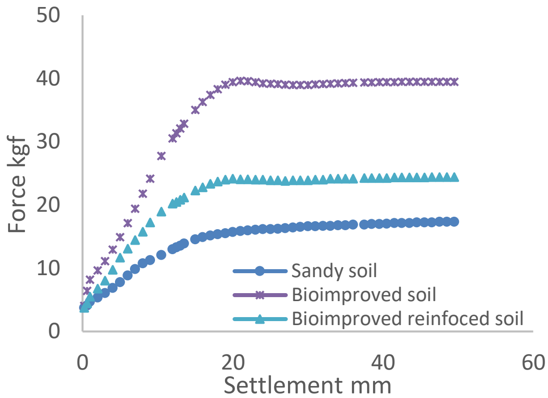

Figure 16. Bio-improved reinforced soil test result

the overall bio-improvement of the reinforced soil caused a more advantageous result in increasing the mechanical characteristics, including its bearing capacity.

4. CONCLUSION

With bacterial sources, which can be a suitable alternative to micropile chemical grout injection. The injection causes bio-cementation of the soil and increases the stiffness and strength of the composite soil. Also, the following results were the output of this process:

•Bio-grout with low viscosity and energy consumption is prepared from renewable sources, and after injection into the soil, it causes soil particles bio cementation.

•Bio-improved soil, with bio-grout injection, caused the connection between the soil particles and increased its bearing capacity by 54.1%. This increase in soil stiffness was also noticeable.

•In the reinforced soil case, the bio-grout injection increased the bearing capacity of the soil by 94% by creating a cover around the bio-micropile. While the non-grouted micropile only increased it by 55%. Also, superplasticizer cement grout injection in micropiles increased its bearing capacity by 112%.

•In a comparative study showed that soil reinforcing with bio-micropiles improved their mechanical characteristics. The bio-grout injection is a renewable and eco-friendly method arison of bio-grout with cement grout, despite the creation of enough cover in micropile due to the stability of bio-grout production resources, its eco-friendliness, the possibility of self-healing of cracks over time in bio-cement cover, bio-grout benefited from better advantages.

•The results of the experiment showed that the bio-improvement method in reinforced soil caused a significant increase in the bearing capacity of the soil. The force-settlement curve showed that the soil stiffness also grew. In this method, the soil's bearing capacity increased by 124%.

•Bio-grout with low viscosity makes gravity injection possible. This injection method is low-cost and reduces energy consumption. However, injecting chemical grout consumes energy while causing environmental pollution.
•According to the warnings of the U.N regarding Global Warning, research to find eco-friendly and sustainable methods is necessary. The bio-micropile usage method can be a suitable alternative to micropile with chemical grout.

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Persian Abstract

چکیده

تهیه و تولید سیمان پرتلند، به‌عنوان یکی از پرمصرف‌ترین مواد در صنعت ساختمان، موجب افزایش آلودگی محیط زیست و تشدید خطر گرمایش جهانی شده است. بهسازی زیستی خاک، یک روش کاملا تجدیدپذیر و سازگار با محیط زیست می‌باشد که در سالیان اخیر مورد توجه پژوهشگران قرار گرفته است . ترسیب کربنات کلسیم ناشی از فرایند زیستی (M.I.C.P) بیشترین سهم تحقیق را برای مسائل بیو-ژئوتکنیکی داشته است. Sporosarcina Pasteurii ،یک میکروارگانیسم تولیدکننده آنزیم اوره‌آز است که در این پژوهش برای بهسازی زیستی خاک ماسه‌ای مورد استفاده قرار گرفت. در این تحقیق مقایسه چگونگی عملکرد دوغاب زیستی و دوغاب سیمانی، در تزریق به درون و اطراف ریزشمع های مسلح‌کننده خاک صورت گرفت. همچنین بهسازی زیستی موضعی و کلی خاک، که تشکیل دهنده یک مقطع مرکب در خاک می‌باشد، مورد پژوهش قرار گرفت . نتایج آزمایش‌ها نشان داد که استفاده از دوغاب زیستی تأثیر بسزایی درافزایش ظرفیت باربری خاک داشت. مسلح کردن خاک باریزشمع زیستی ظرفیت باربری را بیش از ۹٤ درصد افزایش داد. این افزایش در مورد ریزشمع سیمانی ۱۲٦ درصد بود .همچنین نتایج آزمایش‌ها نشان داد که ظرفیت باربری خاک بهسازی کامل زیستی شده و خاک مسلح به‌ترتیب ٥٤ و ۱۲۵ درصد افزایش یافت. این تحقیق نشان داد که استفاده از ریزشمع‌های زیستی می‌تواند روش مناسبی برای جایگزینی مسلح سازی خاک با ریزشمع‌های با تزریق ذوغاب سیمانی باشد.