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Investigating The Effects Of Freeze-Thaw Cycles On The Shear Behavior Of Sand Stabilized By Microbial Induced Carbonate Precipitation (MICP) Method

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Abstract
The MICP method is used as a novel procedure for soil stabilization. One of the important things is to assess how long-lasting new additions are for stabilizing soil. Therefore, this study assesses the impact of freeze-thaw cycles on the strength of sandy soil stabilized using the MICP method. Additionally, variables like confining pressure, the number of freeze-thaw cycles (NC) for FT, temperature changes (T) during each cycle, and the length of the cycles are evaluated. For this purpose, the consolidated-undrained static triaxial tests are used. Taguchi method is applied to design the tests and propose a relationship for predicting the specimens' deviatoric strength (q). The results show that FT cycles reduce the deviatoric strength of samples stabilized by the MICP method. Also, the results of analysis of variance (ANOVA) indicated that the confining pressure, number of freeze-thaw cycles, minimum temperature of freeze-thaw cycles, maximum temperatures of freeze-thaw cycles, and duration of freeze-thaw cycles have, respectively, the highest importance and effect on the q value.

Keywords: MICP; freeze-thaw; deviatoric strength; Taguchi method

1-Introduction

In engineering projects, soil suitable for engineering needs must be improved to achieve high strength and durability. Therefore, more appropriate soil materials may be required for numerous executive initiatives, including building highways, embankment dams, irrigation systems, and drainage networks. As a result, the soil materials that are sometimes suited at the project's building site need to be fortified and upgraded. Weak and inappropriate soil cannot support the project site, and transporting earth resources will become more expensive[1-2]. Considering the population growth, increased demand for soil, and lack of appropriate soil for construction purposes, there is a need for soil improvement. One such method of improving soil quality is soil stabilization. When the strength of the existing soil at the project site is inadequate, soil stabilization can be utilized to enhance the mechanical and physical properties of the existing soil. Cement and lime are widely used additives for soil improvement, but their production is associated with environmental problems [2-8]. MICP is a novel method that uses bacteria to form calcium carbonate crystals and stabilize the soil [8-11]. The process of producing microbiological precipitation of calcium carbonate by applying the calcium carbonate biological precipitation method is based on urea hydrolysis using micro-organisms with urease capability [12-14]. In the method of soil stabilization using traditional stabilizers, these materials are injected into the soil's in-depth layers to increase the soil's strength and stiffness by bonding the soil grains. However, traditional stabilizers are often expensive and difficult to distribute uniformly in the soil. Nevertheless, by using these materials, hazardous substances may penetrate the groundwater table and soil [15-16]. The MICP technique has been used in various fields, including increasing soil strength and stiffness, dust control, and reducing settlement, permeability, and liquefaction When the strength of the existing soil at the project site is inadequate, soil stabilization can be utilized to enhance the mechanical and physical properties of the existing soil. De Jong et al. [9] presented a method to improve the behavior of non-cohesive soil using microbial processes. They used non-destructive testing using shear wave velocity measurements. Also, the undrained-consolidated triaxial test results showed that the samples stabilized by the MICP method had a higher shear behavior with softening strain, initial shear stiffness, and maximum shear strength than the unstabilized samples. SEM images showed the formation of the cement matrix between soil particles with the concentration of bonds forming sedimentary calcite. Furthermore, X-ray examination revealed that calcite makes up the cement linkages.. Gao et al. [17] used the stabilization method based on MICP to control water seepage in irrigation canals and reservoirs built on sandy soil. The findings demonstrated that seepage was successfully stopped by the soil stabilization technique prior to the formation of a shell layer on the sample's exterior. Following bio-treatment, a 10–20 mm thick, hard layer with poor permeability and 5% calcite content developed. The examination of the mercury penetration test showed that the volume and size of soil pores stabilized by the MICP method decreased significantly compared to unstabilized soil. They also found out from the permeability test that the penetration rate of the layers was significantly reduced compared to unstabilized soil. The stabilized soils in different regions are affected by different environmental conditions. Accordingly, the durability of these soils should be investigated. One of the conditions that could cause damage to stabilized soils is the freeze-thaw cycle, which may happen in large areas of the world. So far, much research has been done on the effect of the freeze-thaw cycle on the behavior of soils stabilized by the MICP method. Liu et al. [18] evaluated the effect of different environmental conditions on the stabilized sand by the MICP method. On the stabilized specimen, they applied freeze-thaw cycles for a total of twenty-four hours at temperatures between -18˚C and 23˚C. Then, they performed UCS tests on the samples, the research results showed that after 15 freeze-thaw (FT) cycles, the UCS value was reduced by 50%. Sharma et al. [19], using the UCS, STS, and ultrasonic pulse velocity tests, evaluated the effect of FT cycles on the behavior of sand stabilized by the MICP method. They observed that the UCS reduction was 4% and 34% after 5 and 20 FT cycles, respectively. Also, after 20 FT cycles, the shear modulus of the sand stabilized by the MICP method was reduced by about 80%. Gowthaman et al. [20] performed compressive and shear wave velocity, UCS, and shear strength tests with SEM images and evaluated the effect of FT cycles on the sand soil stabilized by the MICP method (they implemented the soil for stabilizing the slopes). They reported that the sand stabilized by the MICP approach showed a 40% drop in the shear wave velocity after 15 FT cycles. Furthermore, mass loss from FT cycles was minimal in areas where the stabilization process produces roughly 23 wt% of the soil in calcium carbonate. Sun et al. [21] conducted UCS tests to evaluate the effect of FT cycles on the loess soil stabilized by the MICP method. They reported that after 5 FT cycles, the UCS of loess soil stabilized by the MICP method decreased by about 22%. Investigating the performed research in the past reveals that most of them have focused on the influential variables of the MICP method, and research needs to be done on the effect of variables involved in the FT cycles on the behavior of soil stabilized by the MICP method. However, the majority of research studies have incorporated the UCS test to assess the soils that are stabilized by using the MICP method. In this research, the consolidated undrained triaxial tests were conducted on the sand stabilized by the MICP method to evaluate the effects of confining pressure, temperature variation, duration, and the number of freeze-thaw cycles on the shear strength of the specimen stabilized by the MICP method under the FT cycles.

2. Experimental program

2.1. Soil

The grading curve of the used soil for the preparation of the specimens is shown in Figure 1. The soil is classified as poorly graded sand in the unified soil classification system.

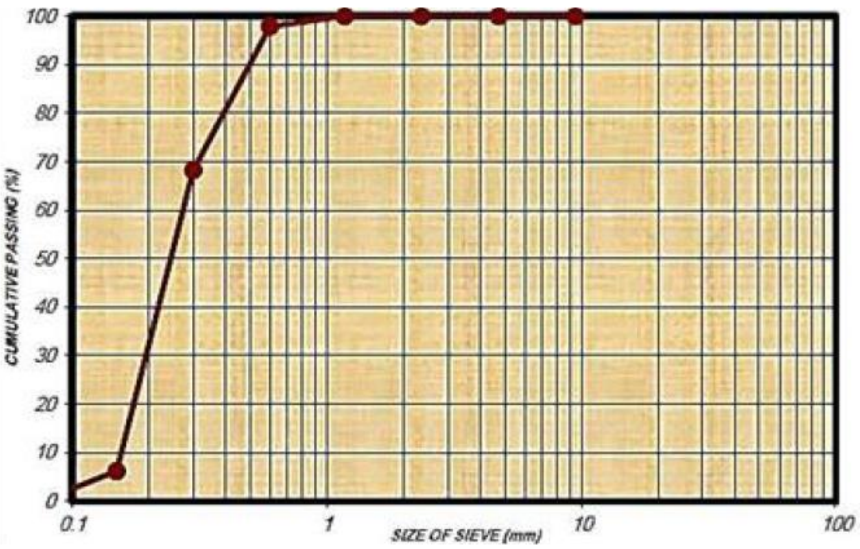


Figure. 1. The grading curve of the used soil

2.2. Sample Preparation

The dry pluviation method was employed to prepare the specimens. The relative density of the specimens was equal to 42%. The bacteria used in this research are from the Bacillus family. To prepare the grout, first, the bacteria were placed in the proper environment, including the yeast extract and ammonium chloride, in the incubatorshaker device. Then, based on the growth curve, the bacteria are separated from the culture environment by the centrifuge device after 48 hours at the end of the growth phase. The urea and calcium chloride, as the matter consumed by the bacteria, are solved in water at 0.5 M concentration and prepared to be used in the experiments. To conduct the test, after executing the flushing phase (flow of distilled water over the specimen with a volume equal to the specimen volume), the bacterial suspension with the culture liquid is poured Three grams of the resulting biomass is distilled in 100 ml of normal NaCl. Next, the urease activity is measured, and the bacteria are placed within an Erlenmeyer flask or container covered with cotton and kept in the refrigerator at 4℃ till the start of the test.on the soil by the gravity injection method (at 1.2 times the volume of pores). Then, by executing the stabilization phase and keeping it for 6 hours, urea and calcium chloride are mixed with a concentration of 0.5 M and added to the soil. Then, the specimen is kept at the laboratory temperature (21℃) for hydrolysis reaction by the bacteria, urea, and calcium chloride. The improvement process by the MICP method includes the flushing, biological, stabilization, and suspension phases, respectively [22]. After the end of the stabilization process, the specimens were cured for 21 days at 23℃ temperatures.

2.3. Taguchi Method

Taguchi's method is used for optimizing the design of experiments and includes four phases: design, implementation, analysis, and verification. Each of the constituent components of the Taguchi method has a specific goal and leads to the optimal design of the experiments. Using Equation (1), the Taguchi method can be used to predict the strength of different specimens.

$$\boldsymbol{\eta} = \boldsymbol{\eta_m} + \sum_{i=1}^{f} (\boldsymbol{\eta_i} + \boldsymbol{\eta_m}) \quad (1)$$

$\boldsymbol{\eta_m}$ is the overall mean value of all Signal/Noise (S/N) ratios in all experimental runs, f is the number of factors and $\boldsymbol{\eta_i}$ is the mean of S/N ratios corresponding to factor levels. Examining the performed tests reveals that factors such as the confining pressure, temperature range of FT cycles, duration, and the number of FT cycles are effective on the soil behavior. Hence, this research aims to investigate the effects of the mentioned factors on the specimen stabilized by the MICP method. For this purpose, consolidated undrained triaxial tests were performed. According to the number of factors considered in this research, the Taguchi method and Minitab software were used to design experiments. In this research, four variables at three levels are incorporated. Considering the conducted research works, the following values are selected for the mentioned factors:

- Confining pressure: 25, 50, and 100 kPa
- Temperature variation in the freeze-thaw cycles: -7℃ to 7℃, -10℃ to 10℃ [23] and -18℃ to 23℃, -23℃ to 23℃ [24]
- Duration of the freeze-thaw cycle: 3, 6, 12, and 24 hours [25]
- Number of the freeze-thaw cycles: 5 [25], 3, 7, 10 [12] and 15 [25]

Ultimately, the experimental program obtained by the Taguchi method is presented as shown in Table 1.

Table 1. Experimental program obtained by the Taguchi method

D (hour)	CP (kPa)	NC	T ℃	Names of samples
6	25	5	(-10,10)	sample 1
12	25	10	(-7,7)	sample 2
24	25	15	(-18,23)	sample 3
3	25	3	(-7,7)	sample 4
3	25	7	(-10,10)	sample 5
12	50	15	(-10,10)	sample 6
24	50	5	(-7,7)	sample 7
6	50	10	(-18,23)	sample 8
12	50	5	(-10,10)	sample 9
6	50	3	(-7,7)	sample 10
6	50	10	(-23,23)	sample 11
3	50	3	(-23,23)	sample 12
12	100	5	(-18,23)	sample 13
24	100	10	(-10,10)	sample 14
6	100	15	(-7,7)	sample 15
-	25	-	-	Control sample (1)
-	50	-	-	Control sample (2)
-	100	-	-	Control sample (3)

3-Results and Discussion

This section discusses the laboratory results, including the stress-strain curve, excess pore water pressure curves, and the deviatoric stress-effective mean stress diagram. The following analysis of variance and sensitivity of different factors on the deviatoric strength of samples stabilized with MICP under FT cycles is performed. Figure 2 shows the stress-strain curves for different specimens.

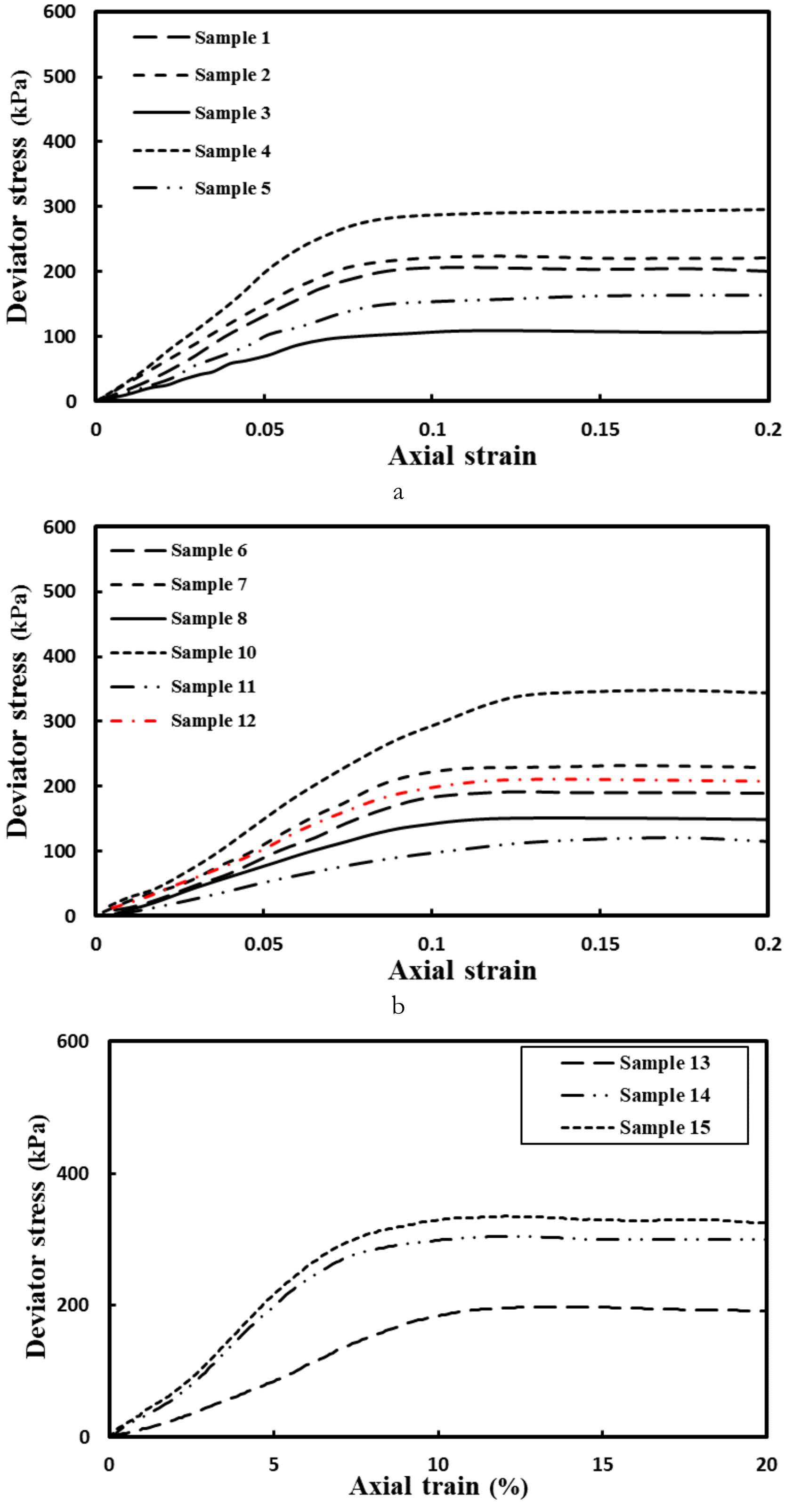
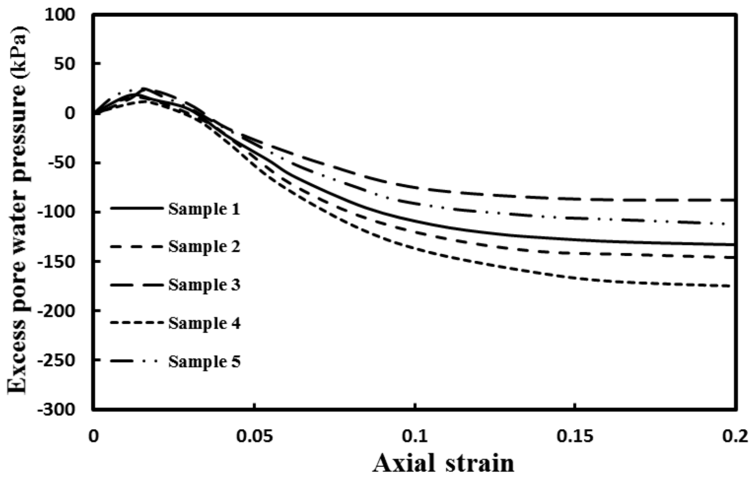


Figure 2 shows the stress-strain pressure curves for different specimens under the confining pressure of a) 25 kPa, b) 50kPa, c) 100 kPa



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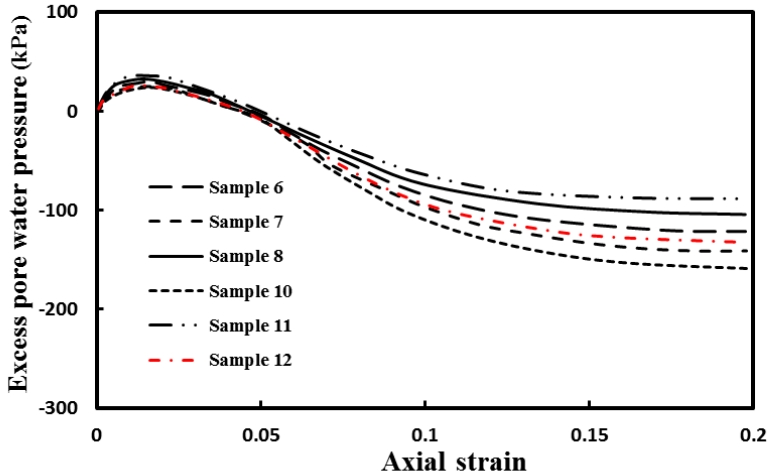

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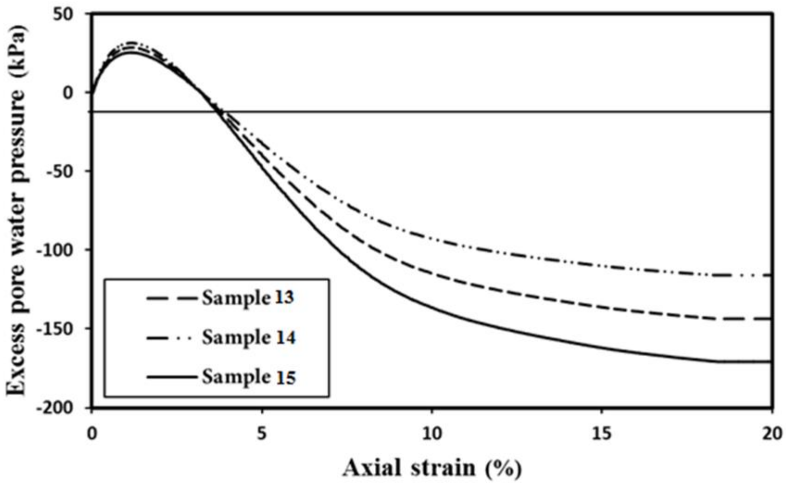

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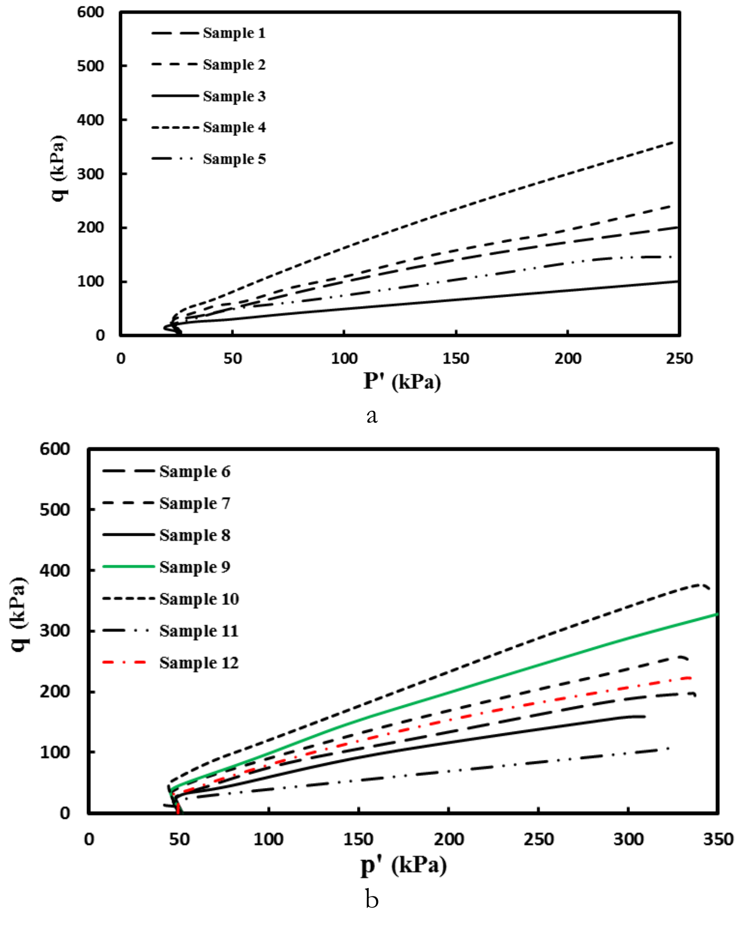
Figure 3: The excess pore water pressure curves for specimens 1 to 15 under the confining pressure of a) 25 kPa, b) 50kPa, c) 100 kPa

Figure 3 shows the excess pore water pressure curves for specimens 1 to 15. As can be seen, the stress-strain diagram of all the specimens has no softening behavior after the maximum strength. However, the loss of strength is due to the weakening of cement bonds caused by freeze-thaw cycles and the formation of excess negative pore water pressure. Due to the pressure created by the ice crystals, cement bonds are weakened. This issue prevents the destruction of cement bonds caused by loading in the specimen from causing much strength loss. In contrast, the negative pore water pressure is formed due to the tendency to dilation due to the destruction of cement bonds during shear loading. This problem ultimately stops strength loss by raising the soil's effective stress. However, as the conditions of freeze-thaw cycles become more critical (increasing the time, number, and temperature of freeze-thaw cycles), the negative pore water pressure decreases. For stabilized soils, destroying the cement bonds and increasing the specimen volume during loading is necessary. This issue manifests as negative pore water pressure during undrained loading. After the freezing-thaw cycles, some of the cement bonds are destroyed. As a result, the tendency to increase volume (dilation) and the excess negative pore water pressure growth are reduced.

Figure 4 shows the deviatoric stress curves regarding effective mean stress for all samples. Examining the deviatoric stress-effective mean stress diagrams shows that initially, the curve inclines to the left. This problem illustrates how effective mean stress decreases under undrained shear pressure. Alternatively, the effective mean stress decreases as a result of the positive surplus pore water pressure created by the void creation and the weak structure of biological cement linkages. As the loading continues, the deviatoric stress-effective mean stress diagrams move to the right. This issue shows an increase in deviatoric stress and effective mean stress. It indicates an increase in strength and the creation of negative excess pore water pressure due to the increase in the effective diameter of the grains, increasing the tendency to dilate. At the end of the graph, the sample reaches the critical state. Put differently, the sample experiences continuous shear displacement and deformation while being subjected to constant excess pore water pressure, constant effective mean stress, and constant deviatoric stress. It is evident from comparing data from the perspective of various confining stresses that for different samples, the deviatoric stress-effective mean stress diagrams approach as the initial confining stress increases. The difference in the graphs of various samples is evident in the confining pressure of 25 kPa. However, the difference between the graphs for the samples tested at a confining stress of 100 kPa is insignificant. The role of initial confining pressure is to close the cracks caused by freeze-thaw cycles.

As previously indicated, the internal structure of the soil matrix-biological stabilizers is weakened by the pressure produced by the production of ice crystals and hydraulic pressure. Thus, the bonds formed are destroyed, and the inner texture of the sample moves outwards with every freeze-thaw cycle. Finally, cracks and micro-cracks are formed in the sample. The distinction in the amount and formation of cracks and microcracks causes a difference in behavior due to various parameters of freeze-thaw cycles. If these cracks and micro-cracks are closed or re-established by an external factor, the behavior differentiation during shear loading is reduced. Applying a high initial confining pressure causes the cracks and microcracks formed in different samples exposed to various parameters of freeze-thaw cycles to be closed. As a result, the behavior of different samples during undrained shear loading becomes closer to each other.



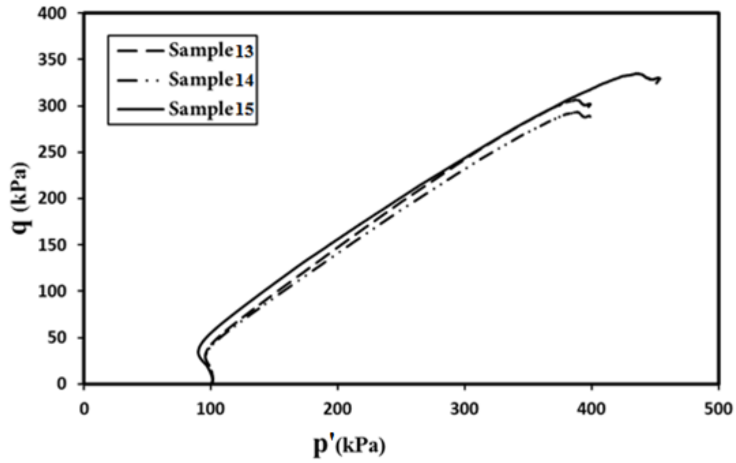


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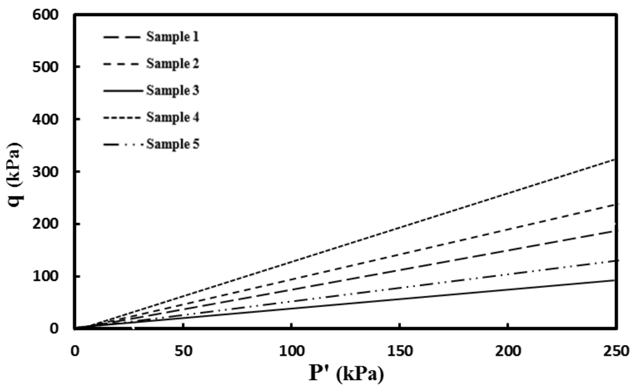
Figure 4: Deviatoric stress-effective mean stress diagram of samples under the confining pressure of a) 25 kPa, b) 50kPa, c) 100 kPa

Figure 5 shows the phase transition line of the deviatoric stress curves in terms of effective mean stress for all samples. Examining results shows that the criticality of freeze-thaw cycle parameters decreases the slope of the phase transition line. A more phase transition slope is typically seen in the line found in denser samples. The parameters of freeze-thaw cycles become essential because of the hydrostatic and ice crystal pressures that wash soil grains away and break the bonds formed by biological stabilization. It can be expected to cause microcracks, cracks, and voids in the sample. In simpler terms, the sample's internal structure becomes weaker after freeze-thaw cycles with a higher destructive potential. As a result, the slope of the phase transition line decreases. The increase in confining pressure due to the closure of cracks reduces the difference in the slope of the phase transition line for the samples under freeze-thaw cycles. In general, increasing the confining pressure decreases the slope of the phase transition line. Increasing confining pressure reduces dilation and volume increase during drained shear loading. Alternatively, the negative excess pore water pressure in undrained loading will decrease. The increase in confining pressure causes the sample's response against shear loading like a loose sample. Accordingly, as the shear behavior becomes loose, the slope of the phase transition line will decrease.



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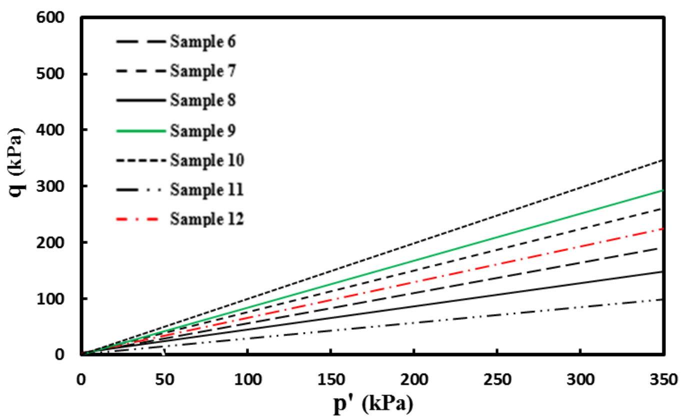

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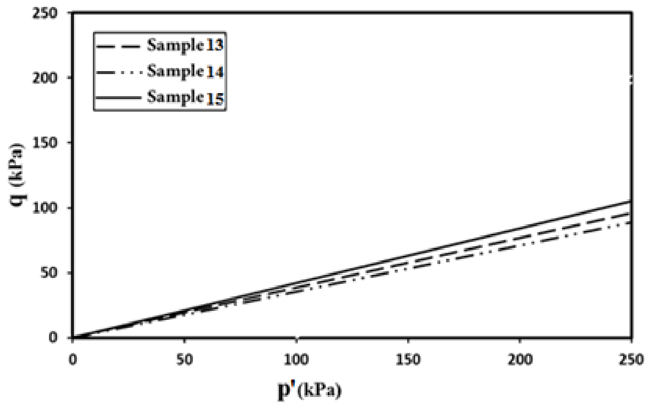

c

Figure 5: The phase transition line in the deviatoric stress-effective mean stress space for all samples under the confining pressure of a) 25 kPa, b) 50kPa, c) 100 kPa

Figure 6 shows the results of (S/N) (signal to noise ratio) analysis with the objective of maximum q value. Findings indicate that confining pressure has the greatest impact on deviatoric strength, after that the number of freeze-thaw cycles, temperature of freeze-thaw cycles, and duration.

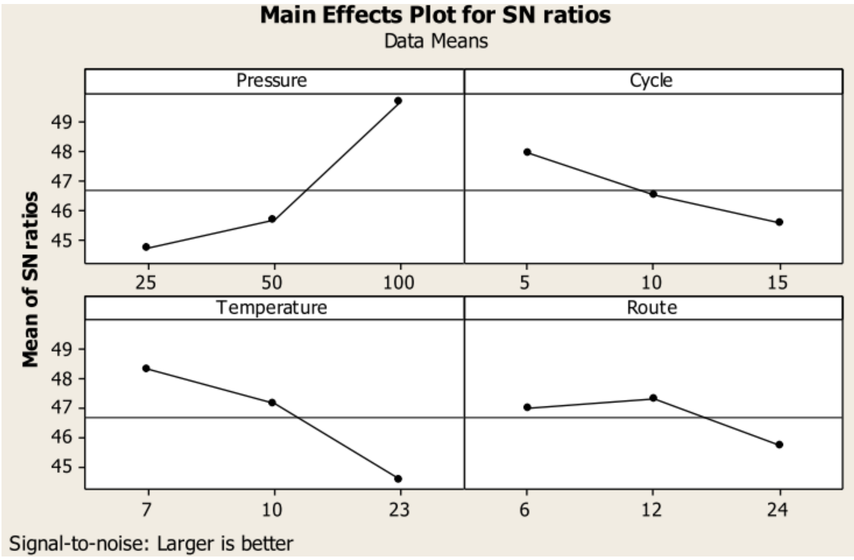

Figure.6. shows the results of (S/N) analysis with the objective of maximum q value

Figure 7 shows the effect of changes in the maximum deviatoric strength in terms of confining pressure and the number of freeze-thaw cycles in the form of two-dimensional contours.

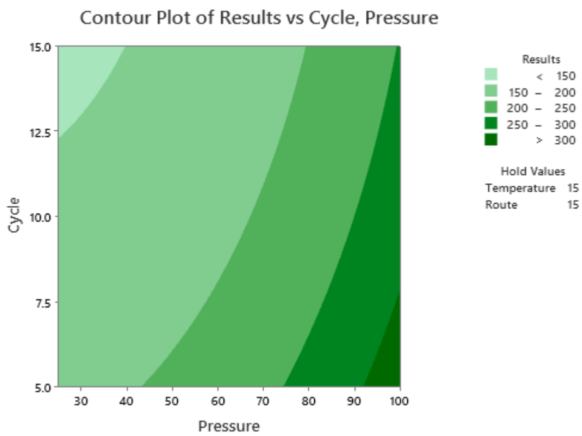

Figure 7: Changes in the maximum deviatoric strength according to the confining pressure and the number of freeze-thaw cycles.

As can be seen, an increase in CP leads to an increase in the strength of MCPI specimens subjected to FT cycles. The effective stress rises with CP, increasing the specimens' shear strength. Conversely, if CP is increased, the specimen's cracks that have developed throughout the FT cycles may be sealed, preventing strength loss. Regarding NC's effect, it may be said that strength decreases as NC increases. For example, when specimen No.3 was subjected to 15 freeze-thaw cycles at the temperature range of -18 to 23 ˚C (the duration of each cycle was taken equal to 24 hours), the maximum deviatoric strength decreased by about 67% (compared to the control sample (1), which was tested at a confining pressure of 25 kPa and was not exposed to freeze-thaw cycles). During freezing, the water volume increased by about 9%. The increase in volume exerts pressure on the inner matrix of the stabilized soil and causes damage to the formed bonds between the soil grains. An increase in NC causes progressive failure within the specimen. The subsequent cycles, while weakening the bonds, cause a larger volume of water to remain within the specimen, and as a result, a higher pressure is exerted during the FT cycles. Using the UCS tests, Sharma et al. [19] evaluated the effect of freeze-thaw cycle numbers on the stabilized sand behavior using the MICP method. They observed that the decrease of UCS after 5 and 20 freeze-thaw cycles equals 4% and 34%, respectively. This issue shows that damage to the cementitious bonds was extensive, and at a certain number of cycles, the decrease in strength was significantly increased. It could be attributed to a weakened cementitious bond and weaker strength of this bond to the pressure exerted by ice crystals. Sun et al. [20] reported that by applying five freeze-thaw cycles, the unconfined pressure of loess soil stabilized by the biological method decreased by about 22%. The strength loss differs depending on the soil type and stabilization level after freeze-thaw cycles. Adeli Ghareh Viran and Binal [25] evaluated the effect of freeze-thaw cycles on the shear strength parameters of sand and swelling soils. They reported that after five freeze-thaw cycles, the cohesion of clayey sand soil and swelling clay soil decreased by about 25% and 18%, respectively. Liu et al. [18] evaluated the effect of different environmental conditions on the stabilized sand by the MICP method. On the stabilized specimen, they applied freeze-thaw cycles for a total of twenty-four hours at temperatures between -18˚C and 23˚C. After that, they put the samples through UCS testing. Following fifteen freeze-thaw (FT) cycles, the UCS value decreased by fifty percent, according to the research findings.

Figure 8 shows the effect of maximum deviatoric strength changes in confining pressure and temperature of freeze-thaw cycles in the form of two-dimensional contours.

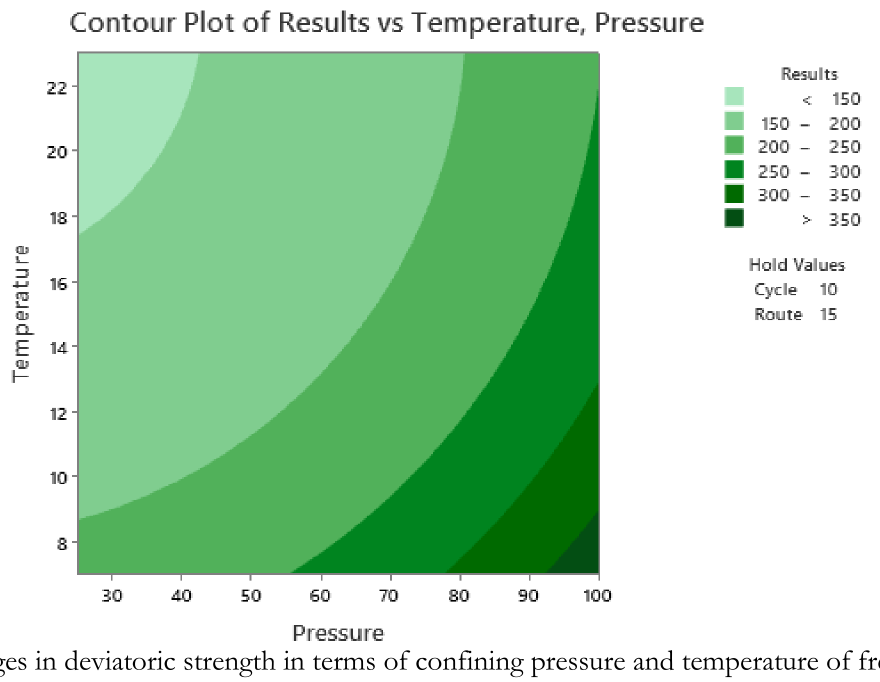

Figure 8: Changes in deviatoric strength in terms of confining pressure and temperature of freeze-thaw cycles

This figure shows that a decrease in the FT cycles' temperature causes reduced strength of the specimens. There is a surface tension force between the soil and water particles. The finer the pores' size, the larger the matrix suction. An increase in the matrix suction causes a decrease in the freezing temperature. Reduction in FT cycles' temperature causes the water in the fine pores, under the impact of high matrix suction, to become frozen. Thus, it applies higher pressure on the bonds formed in the stabilization process.

Figure 9 shows the effect of changes in maximum deviatoric strength in terms of confining pressure and the duration of freeze-thaw cycles in the form of two-dimensional contours.

This figure shows that increasing the time of FT cycles decreases the deviatoric strength. In general, increasing the duration of freeze-thaw cycles provides enough time for the water in the voids to freeze. It should be noted that the time required for temperature transfer into the sample depends on the volume and aspect ratio of the sample.

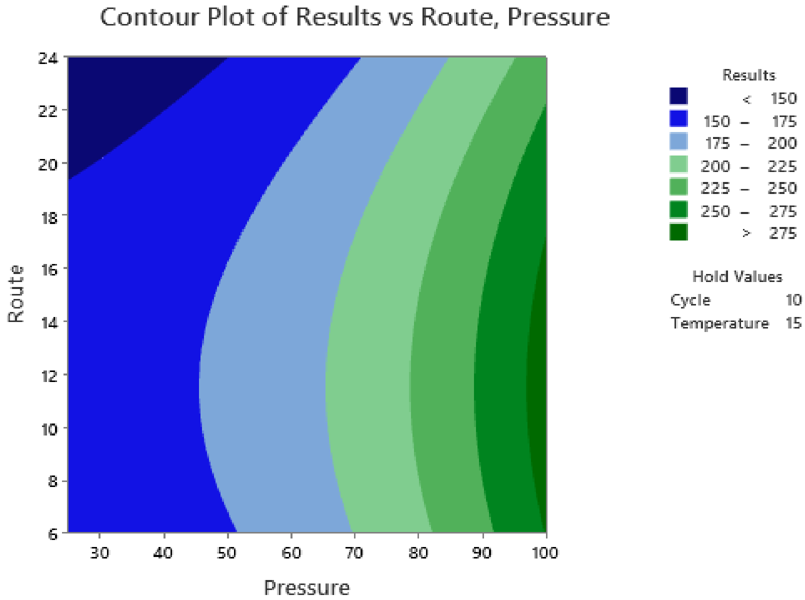

Figure 9: Maximum changes in deviatoric strength according to confining pressure and temperature of freeze-thaw cycles

Table 2 presents the findings of the analysis of variance (ANOVA). The ANOVA findings show that the variables with the greatest effects on strength are CP, NC, temperature, and Rout (each cycle and duration), in that order. As mentioned, the specimen develops several racks and microcracks during the FT cycles. An increase in CP closes these cracks and reduces the FT cycles' adverse effects on the strength. Ta'negonbadi and Noorzad [26] investigated the behavior of stabilized clay under wetting and drying cycles by performing the UCS and direct shear tests. They reported that the W-T cycles have a higher effect on reduced strength in the UCS test than the direct shear test. They stated that this is due to the vertical overburden pressure in the direct shear test, which closes the formed cracks.

Table 2. Analysis of Variance (ANOVA) result

Source	DF	Adj SS	Adj MS	F-Value	P-Value
CP	1	0.41242	0.41242	11.88	0.026
NC	1	0.07609	0.07609	2.19	0.213
T	1	0.06897	0.06897	1.99	0.231
D	1	0.02609	0.02609	0.75	0.435
Error	4	0.13881	0.03470		
Total	8	0.72238			

Equation (2) is presented for prediction of the strength.

$$q=308.111+1.73714CP-3.9666NC+21.555LT+9.777HT-1.5476D \quad 2$$

In Equation (2), CP (confining pressure) is in kPa, NC denotes the FT cycle number, HT denotes the high temperature in centigrade, LT denotes the low temperature in centigrade, D denotes the time of each cycle in hours, and q denotes the deviatoric strength in kPa. The R-squared of Equation (2) for predicting the results equals 95%. Normal probability is utilized to evaluate the model efficiency. The normal error distribution with a zero mean and constant value is shown by the points close to a line. As a result, the model estimates the q value with good accuracy. Equation (2), which is provided by the Taguchi technique, can be used to forecast the outcomes of untested cases. Two specimens were created for this purpose, one for the first state under the following circumstances: the pressure factors equal to 100 kPa, NC equal to 10, temperature range (-18 ˚C to 23 ˚C), Route equal to 24 hours, and for the second state with the following conditions: the pressure factors equal to 50 kPa, NC equal to 15, temperature range (-18 to 23 ^{o}C), Route equal to 24 hours. Then, the results were compared to those predicted by the Taguchi method. The value for q obtained using the experimental methods for the two states No. 1 and 2 was equal to 237 and 119.6 kPa, respectively. The Taguchi method error value for cases 1 and 2 was equal to about 8.5 and 8.9%, respectively. This issue reveals the acceptable accuracy of the Taguchi method in predicting the strength of soil stabilized with the MICP method subjected to the FT cycles.

The results of ANOVA showed that the most significant parameter affecting the deviatoric strength of specimens exposed to freezing-thaw cycles is the confining pressure, the number of cycles, and the temperature and duration of each cycle. Because it creates the fissures brought on by the freezing-thaw cycles, the confining pressure is the most important factor. Therefore, it stops the freezing-thaw cycles' negative effects on deviatoric strength. The most important factor influencing deviatoric strength is the number of freezing-thaw cycles concerning other freezing-thaw cycle factors. Repeated rounds of freezing and thawing allow cracks to propagate and remove components from the specimen. During the future cycles, more water penetrates the specimen, resulting in more pressure on its internal structure due to its freezing, eventually destroying more cement bonds. The temperature of each cycle also controls the amount of frozen water in fine voids within the specimen. Finally, the duration of each cycle is the controller to achieve a temperature balance.

4. Conclusion

In this research, the consolidated-undrained triaxial tests were conducted on the sand stabilized by the MICP method to evaluate the combined effects of confining pressure, changes in temperature, duration of each applied cycle, and the number of freeze-thaw cycles on the shear strength of the specimen stabilized by the MICP method under the FT cycles. The summarized results of these studies are as follows:

1- This research shows that applying the FT cycles reduces the deviatoric strength of the specimens stabilized by the MICP. When specimen No.3 was subjected to 15 freeze-thaw cycles at the temperature range of -18 to 23 ˚C the maximum deviatoric strength decreased by about 67%.

2- A decrease in the FT cycle temperature reduces the strength of stabilized specimens, as predicted by the Taguchi method, the ideal temperature range (-7.7) for the MICP method is suitable, and at a lower temperature than this range, the deviatoric strength drop abruptly increases.

3- The results of variance analysis revealed that the confining pressure, number of freeze-thaw cycles, the temperature of freeze-thaw cycles, and duration of freeze-thaw cycles have the highest importance and effect on the q value.

4- Taguchi method can predict the strength of soil stabilized with the MICP method subjected to the FT cycles. The Taguchi method error value for the two control samples was equal to about 8.5 and 8.9%, respectively.

5- As predicted by Taguchi, the confinement pressure is 100 kPa, the freeze-thaw cycles are 5 and the temperature (-7.7) are present in these cycles for an average of 12 hours. To test the deviatoric strength, a sample with these conditions yielded 393 kPa, and the maximum value was determined to be approximately 386 kPa.

6- The accuracy of the relationship obtained in this study was confirmed by comparing it to other research findings. Liu and Wen demonstrated that resistance decreased by 3.8%, 42%, and 58% after 5, 10 and 15 cycles, respectively. The current research indicates that the decrease in resistance is 21%, 48%, and 67% were accounted for. Moreover, the studies conducted by Sun and Sharma revealed that the reduced resistance was 22% for 5 cycles, and 34% for 15 cycles, and the reduced resistance value in those cycles in this study was 21% and 48%, respectively.

7- Due to freeze-thaw cycles, biological cement bonds are destroyed, and microcracks and voids are formed in the sample. The creation of voids and the deterioration of the cement bond make the sample tend to volume reduction during shear loading. Therefore, the sample will become weaker and looser and produce more positive excess pore water pressure at the beginning of loading.

8- The criticality of freeze-thaw cycle parameters decreases the slope of the phase transition line. Due to the destruction of bonds created by biological stabilization and the washing of soil grains by the pressure of ice crystals and hydraulic pressure, the parameters of freeze-thaw cycles become critical. The increase in confining pressure due to the closure of cracks reduces the difference in the slope of the phase transition line for the samples under freeze-thaw cycles.

9- Due to the destruction of the cement bonds, the freeze-thaw cycles increase the amount of effective stress reduction at the beginning of shear loading, and in the continuation of shear loading, the effective stress increase is reduced due to the reduction of the negative pore water pressure.

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