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Comparative Study of Cement Columns in Improving The Engineering Properties of Silty Soil

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ABSTRACT

This work aims to study the improvement of silty soil properties using different cement column methods. A silty soil was selected from Nineveh Governorate, Iraq, and its engineering properties were determined. Then, the soil was treated with different cement ratios, and samples of the cemented soil were cured for different periods at 25°C. Cement columns used in this study were implemented in the soil in two ways: The first one is the dry method, and the second method involved adding cement to the soil in a solution at a water/cement ratio equal to 0.4%. These columns were implemented inside the soil in a laboratory model and left to cure for 28 days before testing. The results indicated that the dry-implemented cement columns yielded greater improvements in the bearing capacity of the silty soil than those constructed using the wet method, with the bearing capacity increasing by 3 and 2 times for the dry and wet-implemented cement columns, respectively. Also, stress-settlement behavior was improved with cement columns, and the improvement ratio was higher with the dry method than with the wet method. Cement ratios and different curing periods contributed to a significant reduction in the collapse potential and improvement in compressive strength, which is an outcome of the products of pozzolanic reactions. Finally, these methods can represent an ideal solution for treating silty soils locally compared to other techniques that may be costly and time-consuming, especially at great depths.

Keywords:

Silty soil; cement column; bearing capacity; collapse; pozzolanic reactions.

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1. INTRODUCTION

In their natural state (especially when submerged in water), silty soils are characterized by their weak resistance to loads imposed on them, which sometimes leads to failure in structures constructed above [1], [2]. Mainly, structural failure occurs in different types of constructions, either due to bearing capacity failure or soil settlement failure. Therefore, geotechnical engineers resort to improving the properties of these soils to meet specific engineering requirements through several methods, including replacing soil with soils that have better engineering properties, stabilizing the soil (chemically or physically), various types of soil compaction, soil reinforcement, deep mixing, etc. [3-6]. Additionally, soil stabilization by using the deep mixing technique (DMT) is a relatively new technique for improving the engineering properties of soils, especially the weak ones. DMT involves installing columns with various chemical agents, like cement, lime, and fly ash. These columns can be performed in many steps, such as drilling, mixing, and curing (Nicholson, 2014). Further, DMT presents many environmental benefits, such as reducing ground disturbance, lowering carbon footprint, reusing on-site materials, and being less energy-intensive [7]. All these benefits make DMT a valuable technique in sustainable construction and soil enhancement. Soil stabilization using cement columns takes several forms, including mixing soil with cement in a dry state or adding a cement solution to the soil, also known as the wet method. In the dry method, the process involves digging a hole in the soil, extracting the soil, and mixing it with cement and water. After which, the soil is returned to the hole and compacted well. The wet method involves injecting the cement solution into the soil to ensure homogeneous distribution of the cement solution throughout the soil layer whose engineering properties are to be improved [8]. Both methods work to bond soil particles through a series of chemical reactions that lead to improving soil properties and increasing its resilience [9]. Many investigations on the enhancement of weak soils through DMT using cement as a chemical agent have been conducted by many researchers. Dehghanbanadaki et al. (2016) [10] studied the ultimate bearing capacity of rigid footings erected on weak soil, with deep cement-mixing columns. This study was carried out across different length/depth ratios and enhancement ratios. They indicated that mixing columns with end bearing was more widespread than floating columns. Moreover, the failure patterns were changed from punching shear failure for unimproved soil to local failure with progressive cracks and small heave in the improved soil. Yao et al. (2016) [11] conducted a physical model test to examine the settlement of a footing resting on silty soil and enhanced by deep cement mixed columns. Different parameters, including column length and area replacement ratio, were considered. They described that the settlement was reduced as a taller column was used for all area replacement ratios. Furthermore, the settlement values were considerably enhanced by increasing the area replacement ratios for the same column length and applied load. Ni et al. (2021) [12] proposed a T-shaped cement column in their investigation to enhance the bearing capacity of soft fill. The responses of soil with a T-shaped column are measured experimentally. Test results showed that, for a conventional soil-cement column, soil failure always governs the behavior of the composite ground. Using a T-shaped column can change the soil failure mode controlled by the column cap. Zuo et al. (2023) [13] reported that for the same cement percentages of field and laboratory cement columns, the strength of samples in the field was approximately 15 - 55% less than that of the laboratory samples. This behavior may be related to the non-uniformity of the mixing process and the differences in curing conditions. Also, they mentioned that the failure strength of deep soil mixing columns in the field is well correlated with the cement percentages rather than in the laboratory. Locally, silty soils are widespread in Mosul city and are found extensively along both banks of the Tigris River. Due to recent developments in this city, many large engineering projects have begun to be constructed in these areas. The process of replacing silty soil, especially in areas where this soil extends to great depths, causes many economic and environmental problems, especially in large projects. In addition to that, excavation and soil compaction operations during soil replacement cause many problems in the adjacent buildings. Hence, this study gains its scientific importance in understanding the effect of adding cement columns to this type of soil, which in turn represents one of the types of soil that causes many engineering problems. In this study, a deep cement column (DCC) was conducted to enhance the engineering properties of silty soil in two different methods. In the first method, the column was constructed by mixing soil and cement in a dry state (called DDCC), then mixed with (16.2% a moisture content and built in a previously dug hole. While in the second method, the cement was added to the soil column as a slurry with a water/cement ratio equal to (0.4%), called (WDCC). Besides that, a laboratory model was used to evaluate the effectiveness of these methods in improving the properties of silty soils by conducting a plate-bearing test and determining the load-bearing capacity of soils reinforced with both types of cement columns. In addition, several engineering tests were conducted on natural soils and cement-treated soil to determine the effect of cement on these properties and the percentage of cement used in the columns.

2. MATERIALS

Soil used in this study was selected from one of the areas of Nineveh Governorate, namely the Khawaja Khalil area, which is located in the western part of Mosul city. Soil samples were taken from a depth of 1.5 – 2.0 meters below the natural ground surface. Table 1 presents the index and mechanical properties of the natural soil, determined in accordance with the American Society for Testing and Materials (ASTM) standards. Meanwhile, Ordinary Portland cement was used as a chemical binder in this study, and it consisted of the following main components: 53.64% tricalcium silicate (C3S), 18.59% dicalcium silicate (C2S), 8.58% tricalcium aluminate (C3A), and 7.92% tetra-calcium aluminoferrite (C4AF).

Table 1: Chemical, physical, and engineering properties of natural soil.

Test	Specifications	Result	
LL (%)	B.S 1377-2	29	
PL (%)		25	
Soil classification (USCS)	D2487	ML	
Sive analysis	D6913	Gravel %	5
		Sand %	32
Hydrometer	D422	Silt %	46

		Clay %	17
Gs	D854	2.67	
Total soluble salt (%)	Earth manual	3.1	
Gypsum content (%)	USDA-Agricultural	3.7	
Organic matter (%)	D2974	1.9	
EC (μm/cm)	D1125	560	
PH	D4972	8.93	
Max. dry unit weight (kN/m^3)	D698	17	
OMC (%)		16.2	
Unconfined Compressive Strength (kN/m^2)	D2166	87.1	
Collapse potential (%)	D5333	5.4	

3. SAMPLE PREPARATION

During the samples' collection process from the site, they were placed inside tightly sealed plastic bags and transported to the laboratory for testing. Before testing, the soil was dried at a temperature of 60 ºC for 48 hours, then passed through sieve # 4 and placed inside tightly sealed plastic bags, after which it was ready for testing. During the preparation of the natural soil samples used in the mechanical tests, a specific amount of water was added to the previously dried soil, corresponding to the optimum moisture content (16.2%). Then, soil and water were mixed well to ensure moisture was evenly distributed throughout the soil. The mixture was placed inside tightly sealed plastic bags to prevent water evaporation and left for 24 hours. After that, soil samples were compacted inside metal molds, each according to the test used in this study, to achieve the standard proctor density of natural soil (17 kN/m^3).

For cement-treated soil samples, three cement percentages (2, 4, and 6%) were mixed with the soil to achieve the minimum unconfined compressive strength of the cement-treated soil subgrade. These added cement contents were calculated as a percentage of the dry soil weight. After adding the required percentage, soil samples were thoroughly mixed with the dry soil inside a plastic bag until a mixture with a nearly homogeneous color was obtained. Next, water was added in the required amount (16.2%), and the mixture was thoroughly remixed until almost homogeneous. The mixture was left inside the bag for 10 minutes. This initial period ensures that the initial reactions occur. After which, soil samples were compacted inside metal molds to achieve the standard proctor density of natural soil (17 kN/m^3). Then, these samples were extracted from the molds, wrapped in several layers of aluminum foil, and placed inside tightly sealed plastic bags to preserve moisture during the curing period, which ranges from 7 to 56 days at a temperature of 25 ^{o}C. It is worth noting that the moisture content (16.2%) was used for both natural and cement soil, based on the total weight, whether for soil or for soil-cement mixture.

4. LABORATORY MODEL PREPARATION

4.1. The box

For the laboratory model, a cubic metal box with internal dimensions of (500 x 500) mm and a height of 600 mm, previously manufactured by [14], was used to simulate the actual representation of improving the properties of silty soil using cement columns.

4.2. Natural soil compaction

During this step of the laboratory model setup, soil was air-dried at laboratory temperature by spreading it on a bench until a constant water content was reached, then passed through a # 4 sieve. Before soil mixing with water, the moisture content of the air-dried soil was calculated. Then, this value was increased to reach the optimum moisture content (i.e., 16.2%). After that, soil and water were mixed well until a nearly uniform moisture was achieved.

The next step was to place the natural soil mixture inside tightly sealed plastic bags to prevent evaporation. The mixture was left for 24 hours to ensure complete moisture homogeneity, then the soil was remixed and placed in the steel box in layers, compacted using a hydraulic press at a constant speed of 1.0 mm/minute. It is worth noting that the density of each soil layer within the box was checked to obtain the maximum dry unit weight of the natural soil. The surfaces of the successive soil layers were also slightly scratched to achieve good layer overlap, as shown in Figure 1.

After completing the soil preparation process in the box, a foundation model was placed in the center of the box. This square-shaped foundation has dimensions of (100 x 100) mm and a thickness of (6) mm, made from solid steel to achieve a stiff foundation during laboratory testing, especially in the presence of cement columns. The dimensions of the foundation were selected to be compatible with the dimensions of the box, avoiding stress distribution problems on both sides of the foundation.

The compatibility between the dimensions of the foundation and the box requires that the width of the box be approximately five times the width of the foundation, as indicated by [15], [16]. It is worth mentioning that the roughness of the bottom of the foundation was increased to reduce or prevent the foundation from sliding on the soil surface [17]. At the same time, after the foundation was installed in the center of the box, three linear variable differential transformers (LVDTs) were installed on it at an angle of 120 degrees to cover the entire foundation during the loading process and to achieve the required accuracy (see Figure 1).

A rigid loading structure and a manual mechanical press applied load to the foundation at a constant loading rate of 1.0 mm/min [18]. The load was applied until failure was recorded. Data on the applied loads and settlement were recorded using a Z-Load cell and a data logger, and any changes during the test were also monitored.

Fig. 1 Model preparation, testing, and data recording

4.3. Preparation of cement columns of both types DDCC and WDCC

In this phase, a soil-cement column was carried out using the dry method in the laboratory.

Initially, soil was compacted in the box at the optimum moisture content and maximum dry density, as previously described for the preparation of natural soil samples. At the time, the center inside the box was determined to be the center of the cement column. Next, soil was excavated from the box to a diameter of 75 mm and a height of 400 mm using a core drilling machine, as shown in Figure 2. The hole was refilled with a mixture of soil treated with a (4%) cement content in layers, which was previously determined, and with a moisture content equal to (16.2%).

Fig. 2 Steps of the DDCC preparation method

The added soil-cement mixture layers were compacted inside the hole to achieve the maximum dry unit weight of the natural soil and to be compatible with the unit weight values of the surrounding soil. The box was covered with a layer of plastic and a layer of aluminum foil to maintain the moisture of the model, then left to cure for 28 days at laboratory temperature, as shown in Figure 2. Upon completion of the specified curing period, the cover was removed and the foundation was placed on the soil-cement column. Three LVDTs (with a capacity of 50 mm deformation measurement) were also attached to the foundation, as previously indicated, and the model was ready for testing using the same steps as for natural.

For the wet soil-cement column method, the previously mentioned steps were followed to prepare the soil inside the box and dig the hole. A 75 mm diameter, 400 mm long plastic pipe was inserted into the hole after being coated both inside and outside with a thin layer of clean lubricating oil to ensure the soil-cement column remains in place and prevents any collapse during pipe removal. To clarify the effect of these methods on the geotechnical properties of the silty soil, the cement content was constant per unit volume, and the only difference between them was the moisture content. During the implementation of the wet soil-cement column, another 12 mm-diameter tube of the same length (400 mm) was inserted into the casing tube to prepare the cement solution for the entire column. Soil was placed inside the tube, and a cement solution with a water/cement ratio of 0.4% was added through the feed tube, as shown in Figure 3. First, the soil was placed inside the casing tube, and then the cement solution was pumped in while the mixture was compacted. This process continued until the soil-cement column reached the desired height. After which, the casing tube was withdrawn, keeping the soil intact, while the void left by the casing tube was filled with a cemented soil mixture.

Fig. 3 Steps of the WDCC preparation method

In this method, the strength of the soil-cement mixture column depends on the penetration of the cement solution between the soil particles precisely, and to prevent any disturbance in the surrounding soil around the column, cement was pumped into the soil column by connecting the pumping tube to an air pumping device with a very low discharge rate. After that, the setup was left at laboratory temperature for 28 days during an initial curing period, fully wrapped in plastic layers to prevent moisture loss from evaporation. Following that, the plastic layers were removed, and testing equipment was installed. The initial testing involved applying load, deformation readings, and recording for each load to establish the stress-strain relationship, which continued until failure occurred.

5. LABORATORY TESTS

Many tests were conducted on natural and cement-treated silty soils to determine the effectiveness of cement in improving their engineering properties. They also aimed to determine the cement ratio that provides the minimum compressive strength, which is structurally acceptable, that will be used during the preparation of both dry and wet cement columns. These tests were conducted on compacted specimens at the maximum dry unit weight and optimum moisture content of natural soil; they included the following:

- **pH and electrical conductivity**

To monitor pozzolanic reactions and their progression, pH and electrical conductivity tests were performed. These tests were conducted according to the method described by [19] for determining pH and electrical conductivity for natural soil and soil treated with different percentages of cement, with curing periods extended to 56 days at 25 °C.

- **Unconfined compressive strength test**

An unconfined compressive strength test was conducted according to ASTM D-2166 procedure to evaluate the UCS for natural soil samples with the dimensions of (50 mm diameter and 100 mm height). In this test, the load was applied on the sample at a rate of 1 mm/min, continuously until failure. For cement-treated soil samples, the test was conducted at a specific curing period, according to the ASTM D-1633 procedure, at the same rate used for natural soil samples.

- **Collapse potential test**

The collapse potential test is considered an important test for silty soil. This test was conducted on natural and cement-treated soil samples with dimensions of (63.5 mm in diameter and 19 mm in height) according to the procedure listed in ASTM D-5333. The collapse potential index was determined at a stress value of 200 kPa and was calculated according to the following equation:

$$\text{cp}\ (\%) = \frac{\Delta e}{1+e_0} \quad \dots\dots\dots\dots Equ.(1)$$

where:
cp: collapse potential index
e_0: initial void ratio
Δe: change in void ratio

6. RESULTS AND DISCUSSION

6.1. Variation in pH and electrical conductivity values for cement-treated soil samples

Figure 4 shows the results of the pH and electrical conductivity tests for soil samples treated with different cement contents. It can be inferred that adding cement to the soil increased the pH from 8.91 for natural soil to (12.4, 13.4, and 13.54) for soil samples treated with (2, 4, and 6%) cement, respectively, where high pH values facilitate the ion exchange process due to the increase in calcium ions in the soil solution.

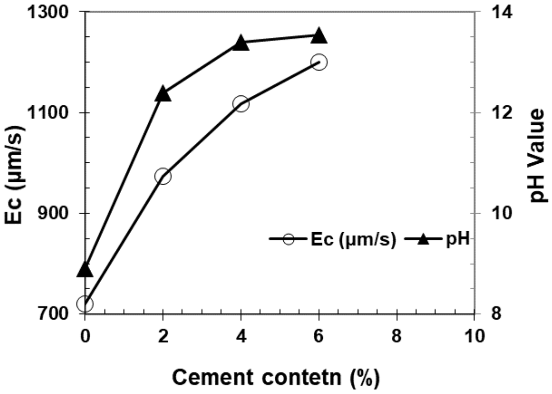

Fig. 4 pH and Ec variation with cement content

Results from [19] and [6] indicated that a pH of 12.4 is necessary to achieve suitable conditions for the formation of cementitious binders via pozzolanic reaction. Consequently, the resistance of soils treated with cement and cured for different curing periods increases. Also, and as can be seen from Figure (5-A), the pH values of cement treated soil samples gradually decreased with increasing curing periods, the higher reduction in pH values occurred for samples treated with 2% cement and cured for 56 days, after which, the pH values reached (9, 9.3 and 9.7) for soil samples treated with (2, 4 and 6%) cement content respectively. [20] concluded that pozzolanic reactions, which cause an increase in soil resistance, can occur up to pH values greater than 9. The reduction in pH of the soil samples treated with cement is associated with decreases in both calcium ions (Ca++) and hydroxyl ions (OH-) over curing periods, which are essential for the formation of pozzolanic reaction products CSH and CAH. Regarding electrical conductivity, the results showed that it followed the same trend as pH, increasing from 720 µm/s in natural soil to 973, 1116, and 1200 µm/s for soil samples treated with 2, 4, and 6% cement content, respectively. The increase in electrical conductivity with increasing cement content is due to the greater concentration of calcium ions (Ca++) in the cement. They also decreased with increasing curing time (see Figure 5-B), with the greatest decrease observed for soil samples treated with 2%

cement and cured for 56 days. This reduction is attributed to the consumption of calcium ions during pozzolanic reactions, as previously mentioned.

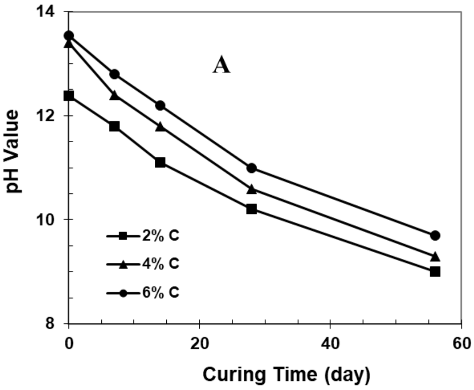

Fig. 5 A: pH variation with curing times

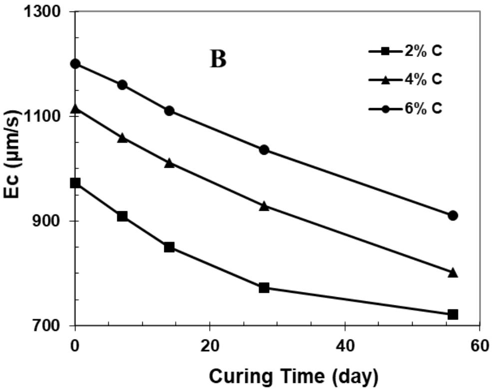

Fig. 5 B: Ec variation with curing times

6.2. Variation of unconfined compressive strength (UCS) values with cement ratios and curing periods

Natural soil was treated with cement contents ranging from 2 to 6% of dry soil weight to meet the minimum strength requirements for a cemented soil subgrade. These samples were subjected to various curing periods ranging from 7 to 56 days at 25°C. Figure 6 shows the variation in the unconfined compressive strength (UCS) of soil samples with both cement content and curing period. The Figure indicates that the UCS of the natural soil samples increased linearly and significantly with increasing cement content. Moreover, the improvement in the unconfined compressive strength for soil samples treated with 2, 4, and 6% cement was approximately (4.5, 11.8, and 14) times the strength of the natural soil for a curing period of 7 days, respectively. Then, the improvement in the UCS of these samples increased to (8.6, 19.6, and 28) times the strength of natural soil at the curing period of 56 days.

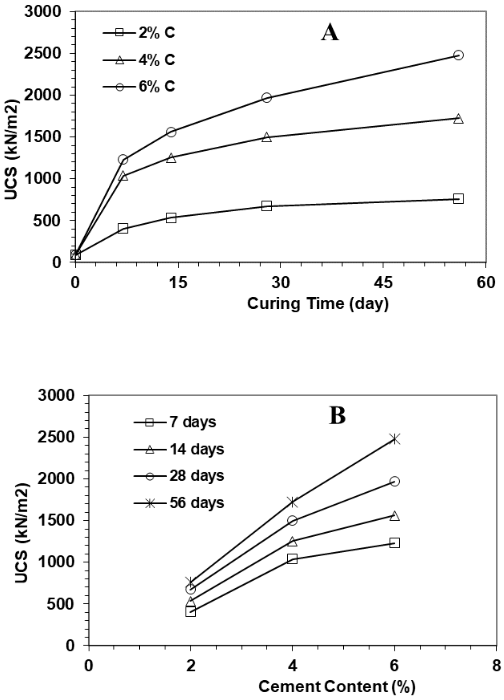

Fig. 6 UCS variation with curing periods (A) and with cement content (B)

The increase in the UCS of the cement-treated samples is related to the chemical reactions between cement and soil, which result in the formation of pozzolanic reaction compounds (calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH)), where the higher the cement percentage, the higher the amount of these compounds, and consequently, the resistance increases. It is also noted from Figure 6 that the curve has an increasing trend in UCS with curing periods, showing a nearly steep slope at short curing periods (e.g., 7 days) for all cement contents. After which, the curve took on a slight slope, increasing slightly up to 56 days. This behavior may be due to the cement hydration process, which occurs rapidly during short curing periods [21], [22]. It is worth noting that the increase in UCS with the addition of cement, curing periods, and the decrease in the values of both pH and electrical conductivity are evidence of the formation of hydration reaction products (CSH and CAH).

To determine the cement content that achieves the minimum compressive strength required for the cemented soil subgrade layer, it was found, as shown in Figure 6, that a 2% cement content across all curing periods did not meet these requirements. While the remaining cement content

(4% and 6%) at curing periods of 28 days or greater satisfies the lower strength requirement for using soil as a sub-base layer for light traffic (Biswal et al., 2020) [23]. From an economic perspective, in using cement as a chemical additive in soil stabilization to improve its engineering properties, the cement content of (4%) was adopted at a curing period of 28 days as the content that obtains the minimum strength requirements for the cemented soil subgrade layer. This content, for a curing period of 28 days, provided a compressive strength of 1500 kN/m2, an increase of about 17 times the unconfined compressive strength of natural soil.

6.3. Collapse potential characteristics of cement-treated soil samples

The collapse potential test was carried out on silty soil samples to evaluate their collapse susceptibility. The collapse potential index was recorded at a vertical stress of 200 kN/m², with natural soil samples showing moderate collapse susceptibility according to ASTM D5333, with a collapse potential index of about 5.4%, which will significantly impact the stability of buildings built on such soils. The addition of cement to silty soil samples increased their collapse potential, transforming their behaviour from collapsed to non-collapsed, even with cement contents as low as 2% for short curing periods (e.g., 7 days). This behavior, as indicated by [24], is due to the cementitious binders formed during pozzolanic reactions, as well as to changes in soil structure that transformed the soil from an open-pore to a denser structure.

6.4. Stress-settlement relationship for natural soil and soil reinforced with cement columns

Figure 7 illustrates the stress-settlement relation curves for three different cases of laboratory model: the natural soil case, the soil improved with a cement column prepared by the dry method (DDCC), and the soil improved with a cement column prepared by the wet method (WDCC). It is noted from Figure 7 that the stress-settlement curves for all studied cases showed the same behavior, in which the measured settlement values continued to increase with the increase in the applied stress values, but with a non-linear relationship. Additionally, the shape of this relationship was a concave curve (Bilinear Elastic Curve); the same behavior was observed by [25] when they used cement columns to reinforce a weak soil layer resting on a rocky layer.

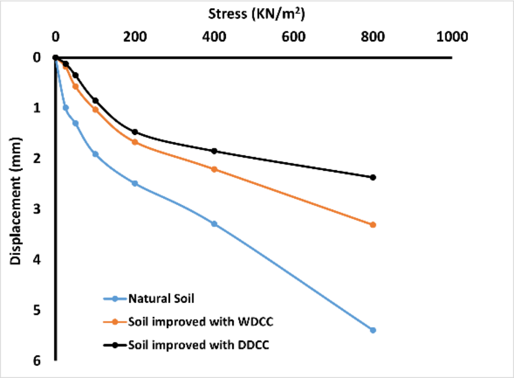

Fig. 7 Stress-settlement curves of natural, DDCC, and WDCC models

Reinforcing natural soil with cement columns, which was executed by different methods, provided different values for the settlement measured at the highest applied stress, where the highest settlement value was (5.39, 3.63, and 2.79) mm at stress of 800 kPa for natural soil, soil reinforced with a cement column executed by the wet method (WDCC), and the soil reinforced with a cement column executed by the dry method (DDCC) respectively.

The DDCC reinforced soil gave lower settlement values than the WDCC reinforced soil during the laboratory test, as shown in the previous Figure. The reason behind that may be related to the homogeneous distribution of cement along the length of the column executed by the dry method (DDCC), also leads to fewer voids distributed along its length (see Figure 8), in which the void ratio decreased from (0.54) in natural soil to (0.3) for the column executed by the dry method and (0.41) for the column executed by the wet method.

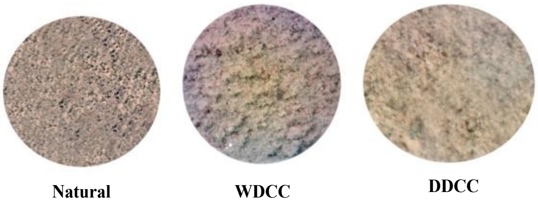

Fig. 8 Microscopic images showing the variation in soil structure

As for the column constructed using the wet method (WDCC), the added moisture content reduced its resistance compared to its counterpart constructed using the dry method [26]. Furthermore, the distribution of the cement solution along the column was inhomogeneous, making the column uneven in strength and void distribution, generating weak areas, especially when the moisture content was high.

It is worth noting that after completing the laboratory test, the laboratory model was drilled to extract the cement columns, as shown in Figure 9. This figure indicates that the column constructed using the dry method (DDCC) was more stable and resistant than the column constructed using the wet method (WDCC). Cores were also taken from these same columns to determine their compressive strength, where the UCS was (795, 638) kPa for the columns constructed using the dry method (DDCC) and the wet method (WDCC), respectively.

WDCC

DDCC

Fig. 9 Images showing the densification of the soil-cement columns

7. CONCLUSION

Through the laboratory study conducted to demonstrate the effect of adding cement on the engineering properties of silty soil, the following important conclusions can be inferred:

1. The process of adding cement to the soil significantly improved its engineering properties, both for soil reinforced with cement columns and for unreinforced soils. The reduction in both pH and electrical conductivity with increasing curing period indicates the formation of pozzolanic reaction products.

2. The use of cement columns contributed to the improvement in the engineering properties of silty soils at different depths. The rate of improvement in these properties depends largely on the method used to install the cement columns in silty soil.

3. Cement columns constructed using the dry cement (DDCC) method improved the engineering properties of the soil more significantly than those constructed using the wet cement method (WDCC). However, these methods have the same cement content in unit volume. This behavior was due to the homogeneous distribution of cement within the dry columns and the high moisture content in the wet columns (0.4% W/C ratio). Load-bearing capacity for soil increased from (190) kPa for the natural soil to (295 and 340) kPa for soil reinforced with columns constructed using wet and dry methods, respectively.

4. Microscopic images revealed a heterogeneity in cement distribution within columns constructed using the wet method compared to those constructed using the dry method. These images also revealed that the wet columns had a higher percentage of voids than the dry columns, which, in turn, provided a clear explanation for the difference in their behavior, improving the properties of the silty soil.

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