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ORIGINAL ARTICLE

Ground improvement using soil–cement columns: Experimental investigation

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Abstract The construction of heavy structures on soils of low relative density is a challenging task. The inclusion of soil–cement columns produced by the deep mixing method is one of the soil stabilizing techniques that could be applied successfully to overcome this challenge. Nevertheless, this technique did not receive a considerable attention in Egypt yet. In the first part of this study, two different natural silty sand soils extracted from the Delta of the River Nile were mixed with cement to prepare samples of different cement doses and different water cement ratios. After curing, the hardened samples were tested and their unconfined compressive strength was investigated. The second part of this study investigates the interaction between a strip footing model and Nile deltaic soil improved by a group of soil–cement columns. Results of the first part of this study showed that the compressive strength of the investigated Nile delta soils could be increased even at lower values of cement doses. Results extracted from the second part of this study showed that a considerable settlement reduction up to 80% could be achieved depending on both the number and the length of the soil–cement columns that is used to improve the soil.

1. Introduction

Sometimes there is a constraint to have constructions on areas considered to be problematic because of the extent of underlying deposits of low strength or unstable soils. In such case, there will be a need to improve the soil using a suitable soil stabilizing technique. The inclusion of soil–cement columns using the deep soil mixing method is one of the stabilizing techniques that have been applied successfully worldwide. The advantage of deep soil mixing method is that it not only improves the strength of ground, but is a superior method for the limitation of settlement. This method mainly depends on increasing the stiffness of natural soil by adding a strengthening admixture material such as cement, lime, gypsum and fly ash. For this purpose, special rotating mixing tools are used which often produce a cylindrical column shaped having a higher strength than the virgin soil. When using cement as an admixture agent, a produced cemented soil material shall be the reaction product of mixing soil with a measured amount of Portland cement

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and water. In this case, the produced soil–cement columns are often compacted to a relatively high density so that their properties become similar to that of soft rock. The modulus of elasticity and unconfined compressive strengths of these columns could be typically 10–20% that of plain concrete [5,9] and hence they can be considered as an engineered low strength concrete columns. As a result, an increase in the soil bearing capacity and a decrease in compressibility shall be gained, which in turn reduces the overall foundation cost by allowing the superstructure to be built on shallow footings rather than pile foundations.

In literature, there are many studies that focused on investigating the optimum dosage of binders to be mixed with particular types of soils to gain a considerable increase in the unconfined strength and to achieve a desired improvement ratio, (e.g., [1,3,4,9,10]). A few or even no one yet has investigated the possibility of stabilizing the Nile delta soil by cement using the mixing method. On the other hand, many other studies concerned about investigating the use of soil stabilization to reduce settlement, to prevent shear deformation of soil, to support excavation, to prevent sliding failure and to mitigate liquefaction, (e.g., [2,6–8]).

Although the technological aspects of deep mixing in terms of machinery and construction have progressed significantly worldwide in the recent years, it is not a common type yet among the soil improvement methods applied in Egypt. Accordingly, there was a need to study the influence of mixing ordinary Portland cement as a hardening agent with Nile delta soils on both the compressive strength of the cemented soil and the interaction between the stabilized soil and foundations. On the beginning, series of tests were conducted to investigate the effect of the soil type, the cement dose and the water cement ratio on the strength of the cemented Nile delta soil. Then, another series of laboratory model tests were carried out by preparing and installing groups of soil–cement columns beneath a rigid steel plate to measure the increase in bearing capacity and reduction of settlement of the stabilized soil.

2. Investigating the soil–cement compressive strength

There are many factors that affect the strength of a soil mixed with cement. Among these factors are the soil type, the cement dose and the water cement ratio. To investigate the effect of soil type, two different types of soil were studied. The soils were taken from two different locations in the middle of Delta of the River Nile, namely "Shobra-alnamla" and "Talbant-qaisar" at Al-Gharbeya governorate. Through this study, the first soil shall be denoted as "Sh" soil and the second soil shall be denoted as "Tal" soil.

To investigate the effect of cement dose on the strength of the mixed cement–soil, a group of tests were conducted on six specimens prepared from soil "Sh". Each specimen was prepared by mixing the soil with a prescribed cement dosage rate. The investigated dosage rates were 160, 200, 240, 300, 340, and 440 kg/m^3. The cement dosage rate can be defined as the weight of binder added per unit volume of the soil to be treated, expressed in kg/m^3. A constant water cement ratio of 1.25 was used for each dosage rate.

Variation of strength of the cemented soil under the effect of different water cement ratios was investigated after a constant curing period. For this purpose, tests were carried out on two sets of specimens. Each set was prepared using one of the aforementioned investigated soils at four different water cement ratios of 0.80, 1.00, 1.25, and 1.50. Both sets were investigated at a constant cement dosage rate of 240 kg/m^3.

2.1. Physical properties of the studied soils

Prior to preparing the specimens, each soil was characterized with respect to its physical properties. The physical properties of both soils were assessed via a classification test program. The tests were conducted in accordance with the ASTM standards. According to the unified soil classification system, both soils are classified as silty sand. Properties of the investigated soils are illustrated in Table 1, and the particle-size distribution is shown in Fig. 1.

2.2. Sample preparation and testing procedure

A laboratory procedure as listed step by step below, was attempted to be developed for preparing, curing and testing the soil mixed specimen applicable to the wet method of soil mixing. This procedure was similar to that described by Shrestha [9]. To prepare the samples, the needed amount of each soil was first dried in oven at 105 °C for 24 h to ensure having soil with zero initial water content. Then, each soil was sieved using sieve No. 8 in order to eliminate any stones and pebbles. Thereafter, the required cement dosage rate of each specimen was achieved by adding and thoroughly mixing a calculated weight of cement with a specific weight of soil. Finally, according to the desired water cement ratio, a prescribed weight of water was added and mixed for about 3–5 min to make cement–water–soil mixture. The cylindrical cemented soil specimens were prepared by pouring the mixture in 3 layers inside thin-wall UPVC molds. Each layer was compacted by hand using a wooden rod to eliminate air pockets and to unite the layers together. All molds have a constant diameter of 100 mm and a length of 150 mm so as to have samples with a shape factor of 1:1.5. The molds also have a longitudinal grove to facilitate extracting the samples after hardening. The filled molds were then covered with plastic bags and stored for a specified curing period of 7 days in a constant temperature of 25 °C. After curing, the specimens were extracted from the molds and left in the air for 1 day before testing. Unconfined compression tests were performed under a testing machine having a maximum load capacity of 250 kN. Each specimen was concentrically loaded until failure. All results were periodically recorded and stored in a computer during the tests by means of a data acquisition system.

3. Investigating the interaction between the stabilized soils and foundations

In literature, most of studies used pure sand or clay for modeling the behavior of foundations rest on improved soil, while only few researches concerned about modeling the behavior of foundations rest on a stabilized natural soil. In this study, both the ground and the soil–cement columns were prepared using the natural soil extracted from "Shobra-alnamla" district. Hence, this soil is denoted in this study by "Sh" as mentioned before. The soil was mixed with an appropriate dose of cement at a prescribed water cement ratio. Both the dosage of cement

Table 1 Properties of the investigated soils.

Properties	"Sh"	"Tal"
Specific gravity	2.68	2.68
Effective size, D10, mm	0.0012	0.004
Median particle size, D50, mm	0.19	0.10
Fines content, %	30.1	43.7
Clay fraction, %	12.0	7.0
Uniformity coefficient, CU	195	–
Coefficient of curvature, CC	6.3	–
Plasticity of fines	Non plastic	Non plastic
Classification (USCS)	SM	SM
Maximum dry unit weight, (γd)max, kN/m^3	16.8	16.91
Minimum dry unit weight, (γd)min, kN/m^3	12.4	11.98
Dry unit weight, gd, kN/m^3	14.28	14.03
Relative density, Dr,%	50	50
Angle of internal friction, φ', degree at	38.0	36.0

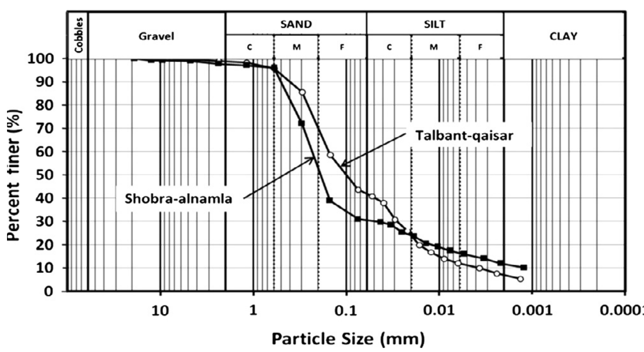

Figure 1 Particle-size distribution of the investigated soils.

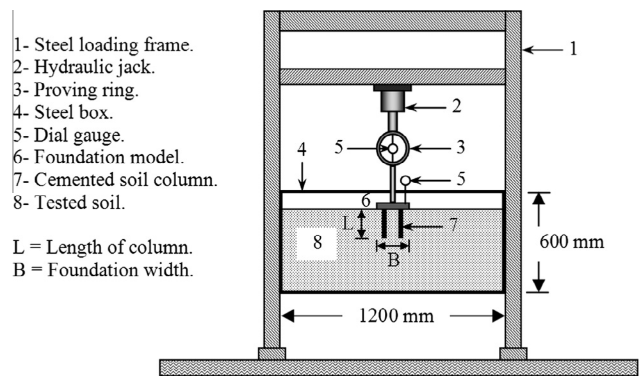

Figure 2 Schematic diagram of the loading system.

and the water cement ratio were chosen so as to ensure preparing a soil–cement mixture with a considerable accepted workability during preparation of the soil–cement columns and to give an appropriate compressive strength during the tests. The steel plate representing the foundation could be concentrically loaded in a steel loading frame. The studied parameters were the columns length, the replacement area ratio of the columns and the curing time.

3.1. Test setup

3.1.1. Preparation of the soil–cement columns

The first part of this study showed that a water cement ratio of 1.25 produced an almost workable mixture that could be poured easily inside the plastic molds. Hence, a water cement ratio of 1.25 was adopted in this part of study. In literature it was reported that a cement dosage rate in the range between 120 and 240 kg/m^3 can be effectively used for stabilizing silty sands, which represent the case of the soil investigated in this study. Moreover, the amount of cement to be used as observed in literatures is typically in the range between 5% and 16% of the weight of the soil to be treated [11]. In addition, from practical and economical points of view, it is better to use a binder dose that accounts for less than 20% of the weight of the soil. Hence, a cement dosage rate of 240 kg/m^3, which is corresponding to a cement ratio of 16.8% was used in this study.

After mixing the soil with the prescribed amounts of cement and water using the same steps mentioned for preparing the specimens of the first part of this study, the soil–cement columns were prepared by pouring and compacting the mixture in layers inside three different groups of thin-wall plastic tubes having a constant diameter of 22 mm. The first group has a length of 100 mm, the second has a length of 145 mm and the third has a length of 200 mm. All tubes have longitudinal grove to facilitate extracting the columns from them. After filling the tubes, they were left in sealed plastic bags for 7 days for curing. Tubes filled with cement–soil mixture to investigate the effect of curing time were left in the sealed bags for 28 days. After curing, the cylindrical soil–cement columns were extracted from the tubes and left in the air for 1 day before starting the tests.

3.1.2. Ground construction

The ground was modeled inside a rigid steel box attached to a steel loading frame that was built especially for this purpose. A schematic diagram of the loading frame and the steel box is illustrated in Fig. 2. The steel box has inside dimensions of 1190 mm length, 490 mm width and a depth of 600 mm. To avoid any lateral movement either during the time of soil placement and columns installation or at the time of loading the scaled foundation models, sides of the steel box were stiffened diagonally by welded steel angles. To allow monitoring the movements of the models during the tests, one side of the box has a detachable 10 mm thick rigid Plexiglas window.

A targeted relative density of 50% was taken into consideration when constructing the ground in the box. The corresponding dry density of the tested "Sh" soil was 1.43 t/m^3. Soil passing from sieve No. 8 was placed inside the steel box in lifts; each lift is 50 mm height. The weight of each lift was assessed depending on both the volume of the space to be filled and the targeted dry density. After leveling the surface of each lift, the soil (when needed) was compacted by tempering with a smooth wooden board. On the same way, all lifts are continued till reaching the prescribed tip level of the soil–cement columns to be tested.

3.1.3. Installation of the soil–cement columns

The soil–cement columns were installed in the steel box following a procedure similar to that described by Bouassida and Porbah [2]. The columns were aligned vertically in their position by means of four different wooden forms manufactured especially for this purpose. Each form has a number of circular holes with diameter of 23 mm spaced equally to give a specified replacement area ratio. The replacement area ratio is defined as the ratio of the total cross section of the columns to the area loaded by the steel plate. The utilized wooden forms have number of holes of 10, 12, 16 and 20, which are corresponding to replacement ratios of 8.7%, 10.4%, 13.9% and 17.3% respectively. Fig. 3 illustrates dimensions of the wooden form, number and distribution of holes in each form, and the corresponding replacement area ratio.

As mentioned in the previous section, the ground was constructed inside the steel box to the level at which the tip of the columns shall rest. Then, the wooden form is held horizontally in position at a suitable level and the soil–cement columns are inserted vertically in each hole. This arrangement ensured distributing the columns at equal spacing between each other. Thereafter, two plastic sheets having a length of 490 mm (which is the same length of the wooden form), thickness of 3 mm and height of 200 mm were aligned vertically at a distance of 5 cm from each side of the wooden form so that the space to be filled with soil is divided into three contiguous parts; two side parts and one mid part. The mid part is the part that contains the soil–cement columns. The weight of soil needed to fill the space of each part was calculated according to the desired relative density. The next layer of soil was firstly placed in both side parts and was tampered to the targeted relative density. Then, the mid part was filled by pouring the needed weight of soil to occupy the space beside and between the soil–cement columns. After that, the plastic sheets were slowly pulled up and a thin wooden rod was used to tamper the soil between and beside the columns to the desired relative density. At this stage, the columns were nearly steady in position, which enabled the wooden form to be carefully removed. The ground construction was continued in layers using the aforementioned process until reaching the top of the columns.

3.1.4. Installation of the strip footing model

A mattress of 10 mm of the same soil was built at the top of the improved ground. The soil mattress was overlaid by a rigid steel plate of 480 mm length, 100 mm width and 20 mm thickness which models the behavior of a strip footing on the improved ground. The width of the plate is adjusted and placed symmetrically at the centerline of the longitudinal direction of the steel box. Each test involved loading the steel plate gradually using a hydraulic jack until reaching soil failure. A steel rod having a semi ball tip was attached to the jack to insure inducing a concentrated load on the steel plate. The steel plate has in the middle of its upper surface a semi bally shaped grove at which the tip of the steel rod shall be in contact with. This allows rotation of the plate in the longitudinal direction of the box during loading process.

3.2. Testing procedure

On the beginning, the tested soils were loaded via the steel plate without improvement in order to compare the behavior of untreated soil with the behavior after installing the soil–cement columns. In all tests, the loading was conducted until reaching a normalized vertical displacement of nearly 25%, at which small increments in the applied load result in relatively big increase in the settlement, which indicates that the soil has reached the failure condition. The loads applied to the foundation model were measured by a digital dial gauge indicator attached to a loading cell. Settlements were measured nearly at the middle of the steel plate using a digital dial gauge attached to the steel box via a rigid metallic arm. Variation of the loading with the settlement was observed and recorded during the tests.

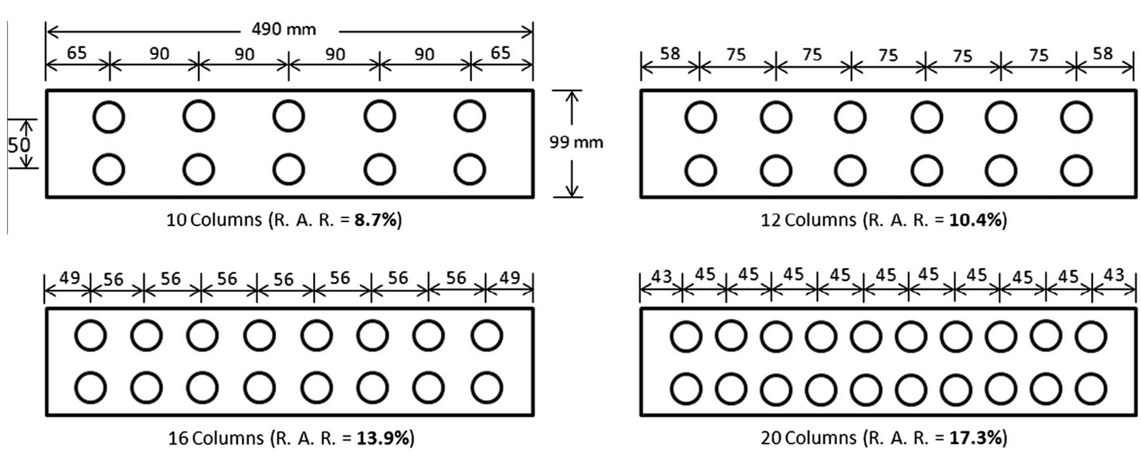

Figure 3 Dimensions of the wooden forms used to arrange and align the cemented soil columns.

4. Analysis and discussion of the results

4.1. Strength of the cemented soils

Fourteen specimens of cemented soil were prepared and tested to study the effect of the water cements ratio, the soil type, and the cement dose on the shear strength of the cemented deltaic soil after 7 days of curing and hardening. The hereinafter subsections discuss the results of these tests in details.

4.1.1. The effect of the water cement ratio on the strength of the cemented soils

The effect of the water cement ratio on the strength of the cemented–soil mixture was investigated for both the "Sh" and the "Tal" soils. Each soil was mixed with a constant cement dosage rate of 240 kg/m^3 and hence, two sets of specimens were tested. The first set was nominated as "Sh-w" and it consisted of four specimens prepared from the "Sh" soil using four different water cement ratios of 0.80, 1.00, 1.25, and 1.50. The second set of specimens was nominated as "Tal-w" and it consisted of four specimens prepared from the "Tal" soil using the same aforementioned four water cement ratios. Figs. 4 and 5 show the effect of the water cement ratio on the compressive strength of the stabilized soils. It can be seen from both figures that as the water cement ratio increases, the compressive strength of the mixed soil decreases. This trend was the same for both types of the tested soils. On the other hand, Figs. 4 and 5 illustrates that the investigated range of the water cement ratio shows nearly a negligible effect on the modulus of elasticity of the hardened soil–cement mixture for both types of the studied soils.

The variation of compressive strength with the water cement ratio for the studied soils was plotted in Fig. 6. The figure shows that the rate of reduction in the compressive strength due to increasing water cement ratio, increases with the increase in water cement ratio. It can be seen, that the difference in strength of both tested soils is significant at a water cement ratio of 0.80. However, such difference tends to decrease with the increase in water cement ratio. This phenomenon can be noticed clearly, since the difference in strength of both tested soils becomes insignificant in this study at a water cement ratio of 1.50.

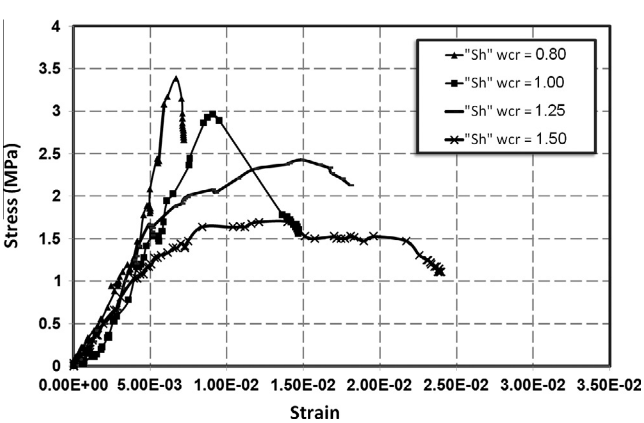

Figure 4 Stress strain relationship of cemented "Sh" soil at different water cement ratios.

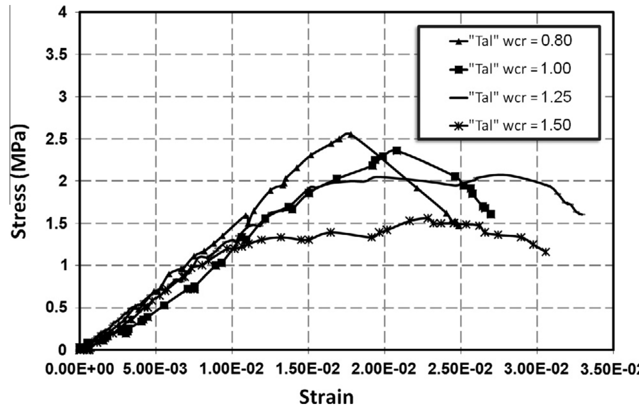

Figure 5 Stress strain relationship of cemented "Tal" soil at different water cement ratios.

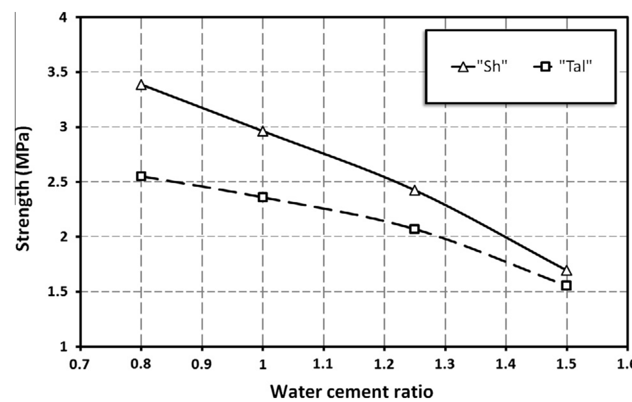

Figure 6 Variation of compressive strength of stabilized soil with water cement ratio.

4.1.2. The effect of the soil type on the compressive strength of the cemented soil

The effect of the mixed soil type was studied by comparing the results obtained from testing samples prepared by mixing cement with the "Sh" soil with the results of samples prepared by also mixing cement with the "Tal" soil. Both soils were prepared using the same cement dosage rate of 240 kg/m^3 but at different prescribed water cement ratios.

From the curves shown in Figs. 4 and 5, it can be seen that at the same water cement ratio, the compressive strength of the samples prepared from the "Sh" soil was higher than the compressive strength of samples prepared from the "Tal" soil. In addition, as shown in Fig. 4, the behavior of the cemented "Sh" soil is brittle at water cement ratio of 0.80 and 1.0, while at higher values of water cement ratios the behavior tends to be ductile. On the other hand, Fig. 5 shows that the behavior of the cemented "Tal" soil is almost ductile at all used values of water cement ratio. Since the "Sh" soil has lower fines content than the "Tal" soil, it can be concluded that the compressive strength and stiffness of the cemented soil decrease with the increase in fines content of the native soil. Finally, it may be interesting to mention that the "Sh" soil has clay content higher than the clay content of the "Tal" soil by about 5%, which means that the fines content has a significant effect rather than the clay content on the stress strain behavior of the studied mixed soils.

4.1.3. The effect of the cement dose on the compressive strength and elasticity modulus of the cemented soil

This section discusses the effect of the cement amount mixed with the soil on the compressive strength of the mixture after 7 days of curing. Six different cement dosage rates were investigated in this study. Each dosage rate was mixed to a predetermined amount of the "Sh" soil at a constant water cement ratio of 1.25. As shown in Fig. 7, the strength, stiffness and brittleness of the cemented soil increase with the increase of cement dose. In addition, this figure shows also that at a cement dose values of 440 and 340 kg/m^3 the behavior of the cemented soil is almost brittle, while at lower doses the behavior tends to be ductile.

Fig. 8 shows that there is an exponential correlation between the compressive strength of the cemented soil and the cement dose. This means that at lower values of the studied range of cement dosage rate an increase in the cement dosage rate leads to a relatively small increase in the compressive strength of the cemented soil, while at higher cement dosage rate, a small increase in the utilized cement dosage rate increases the compressive strength significantly. However, the maximum cement dose utilized in this study is 440 kg/m^3 because it is believed that binder doses higher than 450 kg/m^3, which accounts for nearly 30% of the weight of the studied soils, might not prove economical. According to Fig. 8, the 7-days unconfined compressive strength, qu, in MPa of the hardened cement–soil prepared from the "Sh" soil can be related to the cement dosage rate "CD" in kg/m^3 by the following equation:

$$qu = 1.175e^{(0.003CD)} \quad (1)$$

On the same way, the modulus of elasticity of the hardened "Sh" soil–cement can be calculated from the stress strain curves plotted on Fig. 7. From a practical point of view, it is wise to investigate the effect of the used cement dosage rates "CD" on the secant modulus at 50% of the strain values at failure which can be denoted as "$E_{50\%}$". Fig. 9 shows that there is an exponential relationship between the secant modulus and the studied range of cement doses. Accordingly, after 7 days of curing the secant modulus "$E_{50\%}$" in MPa of the hardened "Sh" soil can be related to the cement dosage rate "CD" in kg/m^3 by the following equation:

$$E_{50\%} = 94.75e^{(0.004CD)} \quad (2)$$

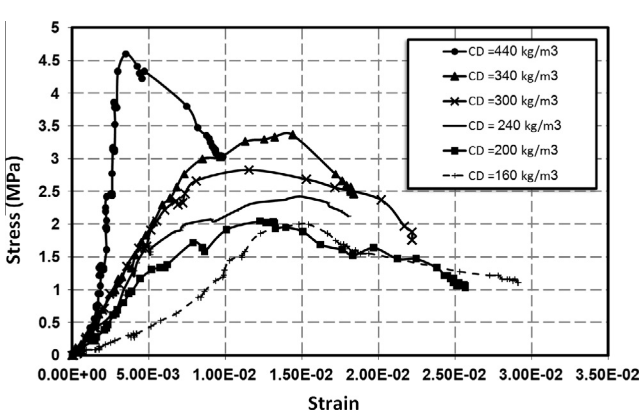

Figure 7 Effect of the cement dose on the compressive strength of the cemented soil.

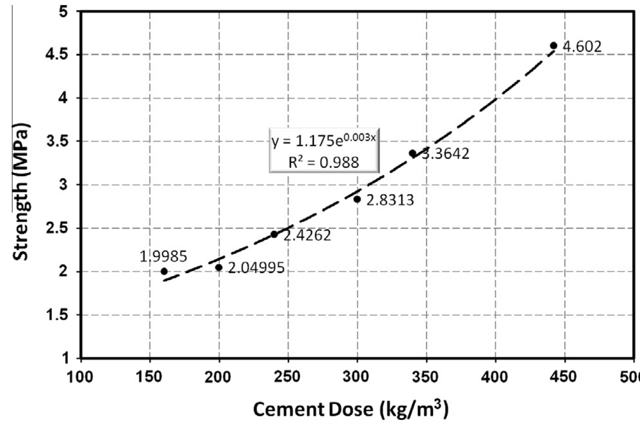

Figure 8 Variation of compressive strength of the cemented soil with the cement dosage rate.

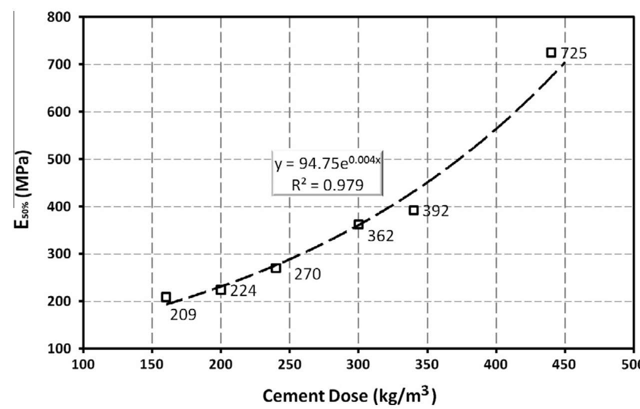

Figure 9 Variation of the secant modulus of the hardened soil with the used cement dose.

4.2. Bearing capacity of the stabilized soil

More than twenty laboratory model tests were carried out in this paper to study the bearing capacity and settlement criteria of a strip foundation model loaded over a stabilized Nile deltaic soil under the effect of different parameters. The investigated parameters are; the replacement area ratio, (a/A), the curing time, and the cemented column length. The hereinafter subsections cover a detailed discussion on the results of the tests.

4.2.1. Effect of the replacement area ratio on the bearing capacity of soil

Figs. 10–12 illustrate the effect of replacement area ratio (a/A) for cemented "Sh" soil columns having lengths of 100, 145 and 200 mm respectively. As expected, it can be seen that increasing the replacement area ratio results in more improvement in the soil behavior. The figures show also that for the same column length, the rate of increase in stiffness of the stabilized tested soil at replacement ratios up to nearly 14% was relatively significant than the rate of increase of stiffness at higher replacement ratios. In addition, when comparing the values at the apex of these curves, it can be seen that the increase in bearing capacity of the improved soil as a result of increasing

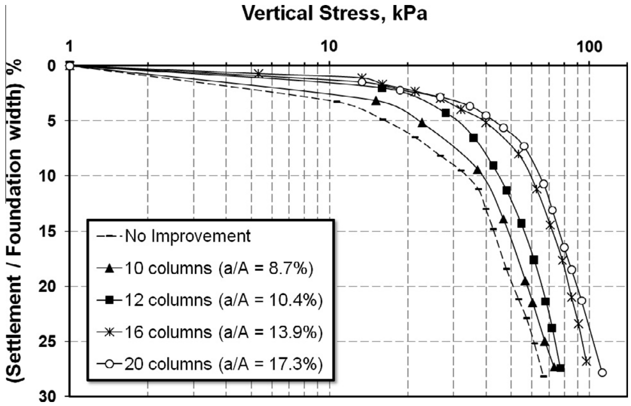

Figure 10 The stress–settlement curves of 100 mm length cemented soil columns at different replacement area ratios.

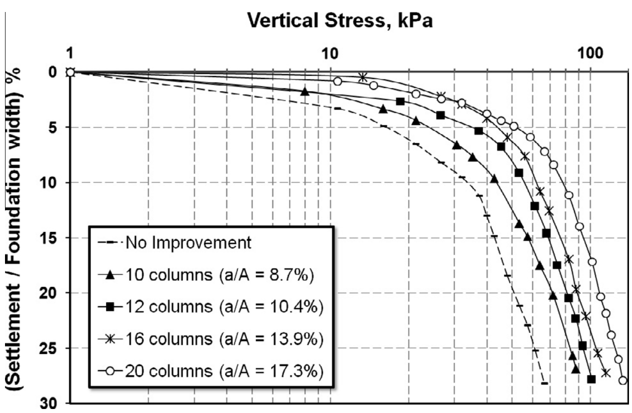

Figure 11 The stress–settlement curves of 145 mm length cemented soil columns at different replacement area ratios.

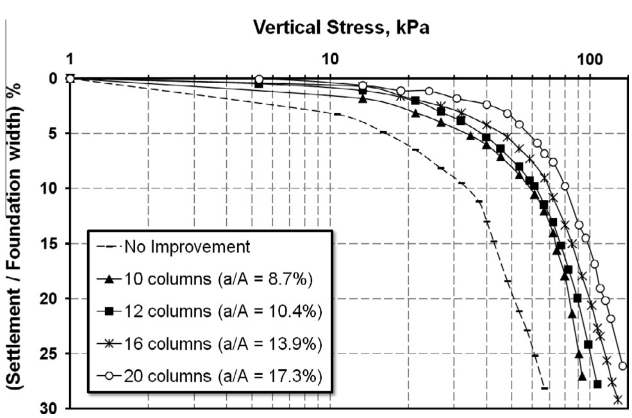

Figure 12 The stress–settlement curves of 200 mm length cemented soil columns at different replacement area ratios.

the replacement area ratio is not clear for column length of 200 mm. On the opposite extreme, when the soil is improved by shorter columns, the increase in the replacement area ratio results in a significant increase in the bearing capacity. Simultaneously, as the replacement area ratio increases, the settlement reduction of the loaded area increases.

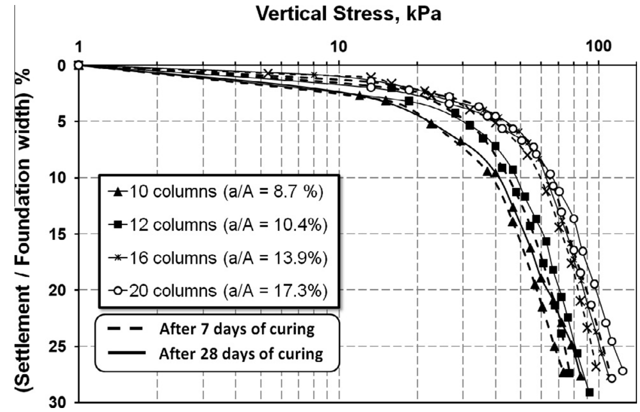

Figure 13 The effect of curing time on the stress settlement curves of the improved soil.

4.2.2. Effect of the curing time on the bearing capacity

The effect of curing time of the cemented columns on behavior of the improved soil was investigated using soil–cement columns of 100 mm prepared from the "Sh" soil. Fig. 13 shows that after 28 days of curing, a slight additional improvement in the soil was achieved. Although the compressive strength of the studied cemented soil was measured only after 7 days in this study, it is believed that a considerable increase in this value was gained after 28 days of curing. According to Shrestha [9], the compressive strength of a soil mixed by cement after 28 days of curing can be nearly twice the compressive strength after 7 days. Shrestha [9] reported also that when using ordinary Portland cement as binder for stabilizing soil, the reaction between the binder and the soil almost finishes within the first month and the final strength is gained. Hence, the achieved increase in bearing capacity in this study believed to be nearly final. In this study, the increase in bearing capacity after 28 days was in the range between 3% and 16% depending on the area replacement ratio.

4.2.3. Effect of the length of the soil–cement columns on the bearing capacity

The effect of the columns length on reducing the settlement of the strip foundation was studied at an applied vertical stress of 50 kPa as shown in Fig. 14. In that figure, the column length (L) is normalized by the width (B) of the area loaded by the

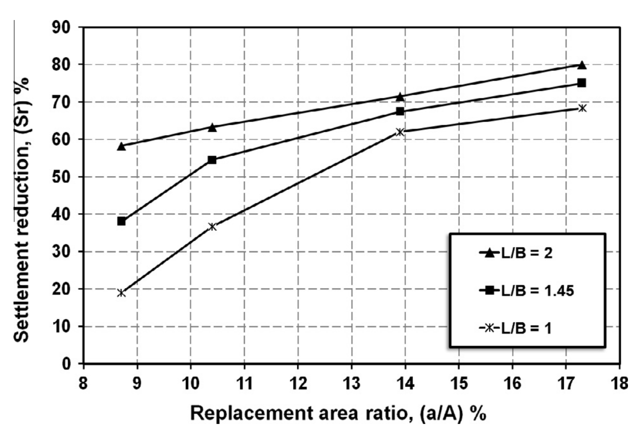

Figure 14 Effect of the columns length of the settlement reduction.

strip footing. It can be seen that a settlement reduction in the range of 20–80% could be achieved depending on both the area replacement ration and the column lengths. It can be noticed also that the normalized soil–cement column length (L/B) has a significant effect on the settlement reduction for replacement area ratio less than about 14%. Such increase becomes less significant with further increase in the replacement area ratio. On the other hand, Fig. 14 clearly demonstrates that the effect of the replacement area ratio in reducing settlement is significant for when (L/B) equals 1.0, while at higher values of (L/B) this effect became relatively insignificant.

5. Summary and conclusions

In this study, laboratory tests were performed on natural silty sand soils extracted from two different locations in the middle of the Nile delta. The first part of the study was devoted toward investigating the ability to improve these soils using the mixing technology method by measuring their compressive strength after hardening of the soils when mixed with cement at different cement dosages and water cement ratios. The second part of this study concerned about studying the load bearing behavior of one of the investigated soils having 50% relative density when stabilized using soil–cement columns prepared from the same soil. The overall conclusions drawn from this study concerning the studied Nile delta soils are as follows:

1. As the water cement ratio increases, the compressive strength of the mixed soil decreases and the decrease in the compressive strength is more significant at higher values of the investigated water cement ratios rather than at lower ones.
2. Although there is a clear difference between the magnitude of compressive strength of both studied soils at water cement ratios of 0.8 and 1.0, this difference tends to be very small at higher values of water cement ratio.
3. The compressive strength and stiffness of stabilized soil decrease with the increase in fines content of the native soil, while the clay content has insignificant effect.
4. The stress strain behavior of the cemented soil is more brittle at lower values of the studied range of water cement ratio, while at higher values, the behavior is ductile.
5. At values of the investigated cement dosage rate, an increase in the cement dose leads to a relatively small increase in the compressive strength of the cemented soil, while at higher cement doses, a small increase in the utilized cement dosage rate increases the compressive strength significantly.
6. The studied range of water cement ratio shows nearly a negligible effect on the modulus of elasticity of the hardened soil–cement mixture, while the cement dosage has a significant effect on the secant modulus at 50% of the strain at failure.
7. At lower values of the studied replacement area ratios, the rate of increase in stiffness of the stabilized soil is relatively bigger than the rate of increase of stiffness at higher replacement ratios.
8. For soil improved by columns having length to foundation width (L/B) of 2.0, increasing the replacement area ratio leads to a relatively small increase in the bearing capacity of the improved soil, while for soil improved by lower (L/B) ratios, increasing the replacement area ratio leads to a significant increase in the bearing capacity.
9. Depending on both the replacement area ratio and the column length, the soil improvement using the soil–cement columns could reduce up to 80% of the maximum settlement of unimproved soil.
10. The Bearing capacity of soil improved by soil–cement columns after 28 days of curing was higher by 3–16% than the bearing capacity of improved soil after 7 days of curing.

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