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Effect of Fines on the Geotechnical Properties of Cement Treated Sandy Soils

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Keywords:
Unconfined compressive strength; Consolidation; Durability; Cement; Sand.

Highlights:

- *The maximum dry density of cemented soils was lower than that of untreated soils.*
- *The highest unconfined shear strength of treated and untreated soils was attained when the soils contained 40% of fines.*
- *The unconfined shear strength increased significantly when cement was added to soils.*
- *Cement decreased the compressibility of soils and increased the durability of soils.*

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Abstract: In nature, sandy soils are not pure since they have various amounts of fines. Generally, when designing a cemented soil system for geotechnical purposes, fines content is not considered. In this study, the behaviors of cement-stabilized sandy soils with various fines content are revealed. Four fines contents, i.e., 30%, 40%, 50%, and 60%, and three cement doses, i.e., 5%, 10%, and 15%, were used in this study. The geotechnical tests, proctor density, consolidation, durability, and unconfined shear strength tests were conducted to reveal the effect of cement and fines contents on sandy soils. The results showed that cement and fines significantly affected the sandy soils' geotechnical properties. The soil strength increased as cement contents increased, whatever the fines content was due to the hydration of cement and the pozzolanic reactions. On the other hand, the strength increased as the fines increased until 40% and then dropped because fines work as filler, and when they increased more than 40%, they pushed the sand particles far from each other.

تأثير المواد الناعمة على الخواص الجيوتكنيكية للتربة الرملية المعالجة بالاسمنت

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الخلاصة

لا تتواجد التربة الرملية في الطبيعة بصورة نقية لأنها تحتوي على كميات مختلفة من المواد الناعمة. بشكل عام، عند تصميم نظام التربة المعالجة بالاسمنت للأغراض الجيوتقنية، لا يؤخذ في الاعتبار محتوى المواد الناعمة. في هذه الدراسة سيتم الكشف عن سلوكيات التربة الرملية المعالجة بالاسمنت المستقرة ذات محتوى مختلف من المواد الناعمة. في هذه الدراسة تم استخدام أربع نسب من المواد الناعمة ٣٠٪، ٤٠٪، ٥٠٪، ٦٠٪ وثلاث نسب للاسمنت ٥٪، ١٠٪، و١٥٪. تم إجراء الاختبارات الجيوتقنية وكثافة الحدل والتماسك والمتانة واختبارات مقاومة القص غير المحصورة للكشف عن تأثير نسبة الأسمنت والمواد الناعمة على التربة الرملية. أظهرت النتائج أن الأسمنت والمواد الناعمة تؤثر بشكل كبير على الخواص الجيوتقنية للتربة الرملية. وتزداد قوة التربة مع زيادة محتوى الأسمنت مهما كان محتوى المواد الناعمة بسبب عملية الاماهة للاسمنت والتفاعلات البوزولانية. ومن ناحية أخرى تزداد القوة مع زيادة المواد الناعمة حتى ٤٠٪ ثم تنخفض لأنها تعمل كمادة مالئة وعندما تزيد أكثر من ٤٠٪ تدفع حبيبات الرمل بعيداً عن بعضها البعض.

الكلمات الدالة: قوة الضغط غير المحصورة، التماسك، المتانة، الأسمنت، الرمل.

1.INTRODUCTION

Soil improvement is widely used to decrease soil permeability, increase shear strength, decrease compressibility, and increase soil durability or decrease erodibility. The chemical stabilizers techniques, such as cement and lime, are considered significant techniques used for sandy soil stabilization or improvement [1, 2]. The type of sandy soil could affect the efficiency of the cement stabilization technique in addition to other factors, such as the type of cement and cement doses [3]. The type of sandy soil depends on the fines proportion and for classified into three main classes: poorly graded, well-graded, and gap graded, since there is no pure sand in nature [4]. The optimum dose of cement to produce optimal properties of soils is different for each type of soil [5]. Moreover, the amount of cement could change the soil's behavior. A small dose of cement, less than 1%, could make sandy soils behave like loose sand and exhibit strain-hardening behavior, while a higher amount of cement, more than 3%, leads the sand to behave like dense sand and exhibit strain-softening behavior [6]. Even though the efficiency of cement for soil stabilization is increased as the cement contents increase, 2% of cement was enough to increase the bearing capacity of sandy soil 30 times that of the untreated soil [7]. Hassan Sharafia [8] stated that 3% of cement significantly increased the CBR, while 9% of cement was considered the optimum dose to increase the unconfined shear strength of the sandy soil used. Bushra Albusoda [9] revealed the cement's effect on the soil's liquid limit. When cement was added up to 12%, the liquid limit was reduced by 22% compared to the untreated soil. Moreover, 4% of cement did not show a noticeable effect on the internal friction angle of sand, while it increased the cohesion from zero to 66 KPa. The collapsibility potential was reduced by 50% when 8% of cement was used. Using doses of cement higher than the optimum could negligibly affect the soil shear strength [10]. The existence of fines with uniformly distributed sand particles could generate problematic sandy soils. In this study, the effect of cement on different sandy soils and the effect of fines on the cement-stabilized sandy soils will be investigated. Most of the previous studies focused on the effect of cement on pure sand. However, few studies investigated the effect of fines on cement-stabilized sandy soils. Many studies were conducted to reveal the impact of fines content on the geotechnical properties of sandy soils [11-13]. The studies showed that fines increased the cohesion of sand and decreased the internal friction angle. Yong Wang [14] and Eseller-Bayat [15] stated that the liquefaction resistance decreased as the fines content increased up to 30% and 10%, respectively. The deviator stress was decreased when the fines content increased [16]. The effect of fines on the behavior of untreated soil has been clearly explored in previous studies [11, 12, 17, 18]. Previous studies showed that fines content significantly affected untreated soils. However, a lack of studies have been done on the effect of fines content on cement-stabilized sandy soils, making it imperative to explore it. Sand is generally considered an unreacted material, so the hydration of cement is the main factor in gaining the strength of treated sand with cement. Adding fines, such as montmorillonite or kaolinite, could change this assumption since studies are showing that cement reacts with these minerals. Consoli [19] studied the effect of fines in cement-stabilized soil using fines proportions up to 30%. Sung-Woo Moon [3] used small fines proportions of up to 5%. The present study explores the effect of fines with four percentages, i.e., 30, 40, 50, and 60%, on the geotechnical properties of cement-stabilized sandy soils with three percentages of cement: 5, 10, and 15%.

2.MATERIALS AND METHODOLOGY

The soil used in this study is artificial, containing various amounts of fines 30, 40, 50, and 70 to represent the study area soil. Four soils were prepared in the lab depending on the fines amount in the soil. The geotechnical and chemical properties and the grain size distribution curves of these soils and cement are presented in Tables 1 and 2 and Fig. 1, respectively. These soils represent the soil of Thi Qar Province, south of Iraq. It is located at 31.1042° N, 46.3625° E. Figure 2 shows the study area.

2.1.Sample Preparation

Standard specimens were prepared, i.e., the dry, untreated soil specimens. These specimens contained different amounts of fines, i.e., 30, 40, 50, and 60 % by the total weight of soil, as clarified in Table 3. Soils were mixed with three amounts of cement: 5, 10, and 15 %. These percentages were chosen based on previous studies since the range of cement used for soil stabilization for sandy soils was between 5% and 15% [20-23]. The treated soils were mixed with cement without adding water using a mixer for 5 minutes to ensure a homogenous mix. Then, water was added gradually to the dry mix using the optimum water content from the compaction test and mixed for another 5 minutes. Finally, these mixtures were molded in an unconfined compressive strength mold and cured for 28 days, followed by the ASTM D2166/D2166M – 13.

Table 1 The Geotechnical Properties of the Study Soils.

Property	Specifications	Soil I	Soil II	Soil III	Soil IV
#4		100	100	100	100
#200	ASTM D422	30	40	50	60
D50		0.25	0.18	0.08	0.045
Clay fraction %	ASTM D422	9.02	12.03	15.03	18.04
Silt %	ASTM D422	19.97	26.97	33.96	40.95
Liquid limit LL (%)		39	41	42	44
Plastic limit PL (%)	ASTM D4318	NP	NP	NP	22.24
Plasticity index PI (%)				,	21.76
Specific gravity SG	ASTM D854	2.65	2.66	2.68	2.69
USCS	ASTM D2487	SM	SM	SM	ML
Maximum dry density MDD (gm/cm3)	ASTM D698	1.91	1.88	1.84	1.78
Optimum moisture content OMC %		9.5	10	10.5	11
UCS (Mpa)	ASTM D2166	0.427	0.565	0.44	0.326
Stiffness (MPa)	ASTM D6758	0.285	0.314	0.366	0.296

Table 2 The Geotechnical Properties of the Fines Used in this Study.

Properties	Value	Specifications
clay fraction%	30	ASTM D422
Silt fraction %	70	ASTM D422
L.L %	35	ASTM D4318
P.I %	10	ASTM D4318
G.S	2.69	ASTM D854
MDD (g/cm3)	1.72	ASTM D698
OMC %	9	ASTM D698

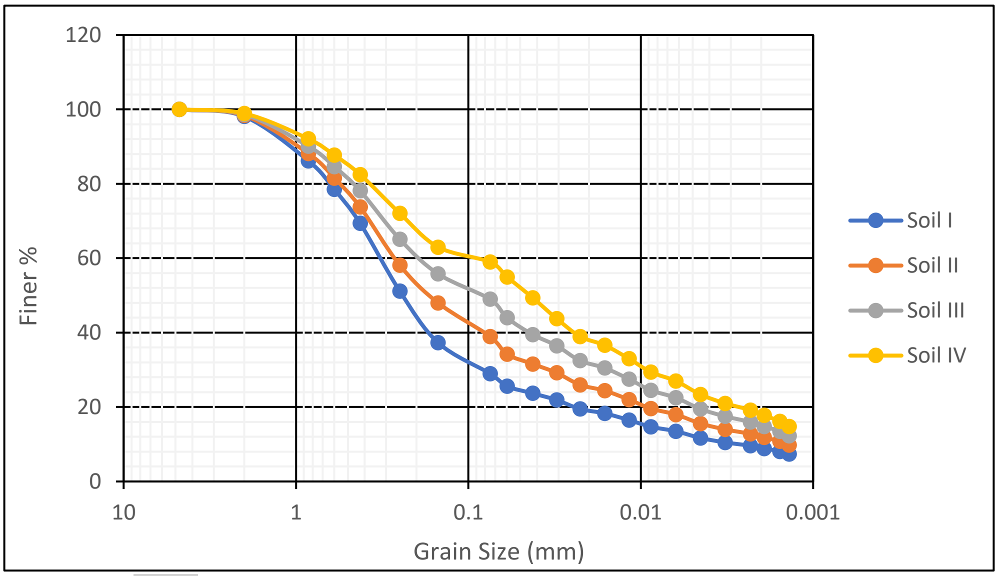

Fig.1 The Grain Size Distribution Curves for the Studied Soils.

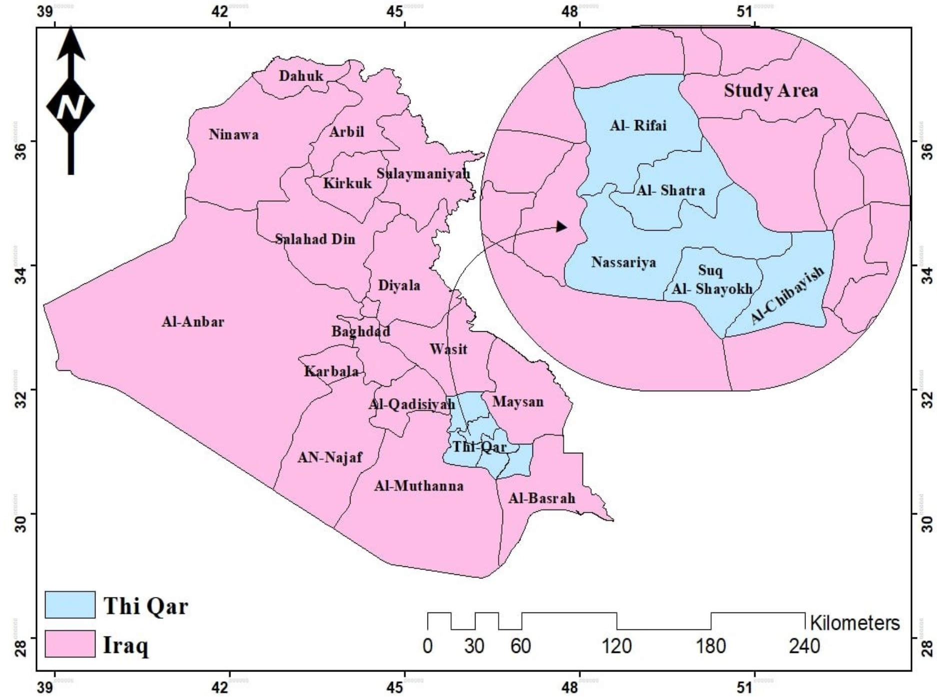

Fig.2 Drawn Map for the Area of Study.

Table 3 Untreated and Treated Soil with Cement.

No.	Specimen name	Description	Percent of sand	Percent of fines	Percent of cement
1	Soil I-C0	70S 30F 0C	70	30	0
2	Soil I-C5	70S 30F 5C			5
3	Soil I-C10	70S 30F 10C			10
4	Soil I-C15	70S 30F 15C			15
5	Soil II-C0	60S 40F 0C	60	40	0
6	Soil II-C5	60S 40F 5C			6
7	Soil II-C10	60S 40F 10C			9
8	Soil II-C15	60S 40F 15C			12
9	Soil III-C0	50S 50F 0C	50	50	0
10	Soil III-C5	50S 50F 5C			6
11	Soil III-C10	50S 50F 10C			9
12	Soil III-C15	50S 50F 15C			12
13	Soil IV-C0	40S 60F 0C	40	60	0
14	Soil IV-C5	40S 60F 5C			6
15	Soil IV-C10	40S 60F 10C			9
16	Soil IV-C15	40S 60F 15C			12

2.2.Testing Program

The testing program of the present study included physical and mechanical tests. The physical and mechanical tests are unconfined compression, proctor compaction, consolidation, and durability. All tests were conducted due to ASTM, as shown in Table 4. A compaction test was first conducted for treated and untreated specimens to specify the maximum dry density MDD and optimum water content OMC for all soil for other tests. Unconfined compressive test UCS and consolidation test were conducted for all untreated and treated soils with different cement contents, i.e., 5, 10, and 15%. A durability test was conducted for untreated and treated soils with 10% cement, considered the optimum dose of cement that produces the optimum unconfined compressive strength.

Table 4 ASTM Specification Followed for Conducting the Tests of the Study.

Test	Specification
Compaction test	ASTM D698
UCS	ASTM D2166/D2166M
Durability	ASTM D559/D559M
Consolidation	ASTM D2435/D2435M

3.RESULTS AND DISCUSSION

The present study conducted an extensive testing program to show the geotechnical properties of untreated and cement-treated sandy soils with various fines content. The results of all tests were discussed, analyzed, and explained using graphs and tables. The physical properties of sandy soils were first found.

3.1.The Effect of Cement and Fines Content on the Compatibility of Sandy Soils

The maximum dry density MDD and optimum moisture content OMC for the four studied soils, i.e., Soil I, Soil II, Soil III, and Soil IV, have been measured using the standard proctor compaction test. The results showed that the MDD increased from 1.87 g/cm3 to 1.88 g/cm3 as the fines increased from 30 % to 40 % by the dry weight of the soil. The MDD decreased from 1.88 g/cm3 to 1.78 g/cm3 when fines content increased from 40 % to 60 %. More fines content was tested to perceive the soil behavior clearly. Two percentages less than 30 % were tested: 20, 0 %, and one percentage greater than 60 %, i.e., 70%. The results approved that 40 % of fines represented the optimum percentage to achieve maximum dry density of soil, as shown in Fig. 3. When fines were added to the pure sand, fine particles were initiated to fill the voids. At 40% of fines, voids between sand particles were completely filled with the fines. Beyond that, fine particles started to push sand particles far from each other, reducing the soil's MDD. The OMC showed an unclear change when fines content varied. It slightly increased when fines increased from 0 to 70 %, as shown in Fig. 4, due to fines' high water retention capability [24]. On the other hand, the results showed that the MDD for all untreated soils was higher than treated soils, as shown in Fig. 5. The MDD decreased as the cement content increased. The reduction in MDD values was 3.1% for Soils I, II, and III and 1.7% for Soil IV. The OMC slightly increased from about 9% to 11% as an average for all soils, as shown in Fig. 6. The chemical reactions of the cement-soil mixture could be the main reason for reducing the MDD of treated soils. Ca2++ introduced to the soil by the cement needs more water to be mobilized to let the exchange cation reaction continue, increasing the optimum moisture content of the treated soil [25]. Soil particles began to agglomerate and flocculate when the exchange cation reaction continued, producing coarser soils with higher void ratios and lower densities [26].

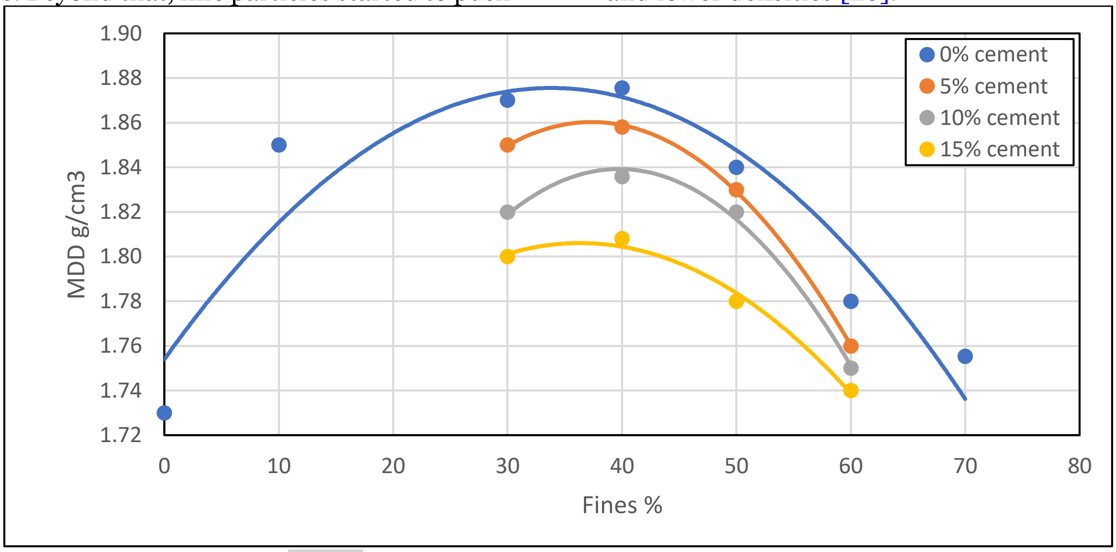

Fig. 3 The Effect of Fines on the MDD of Soil.

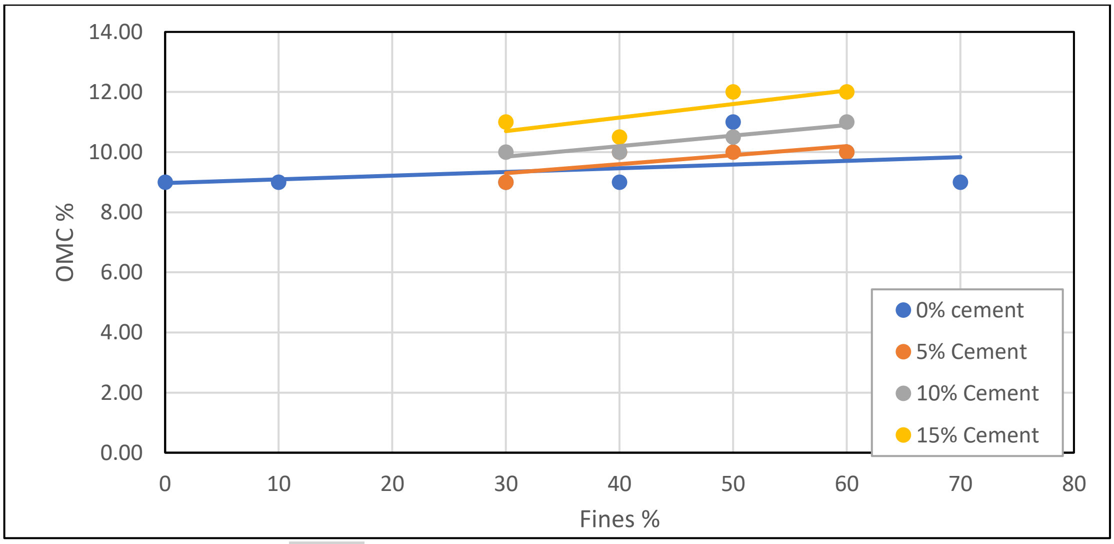

Fig. 4 The Effect of Fines on the OMC of Soil.

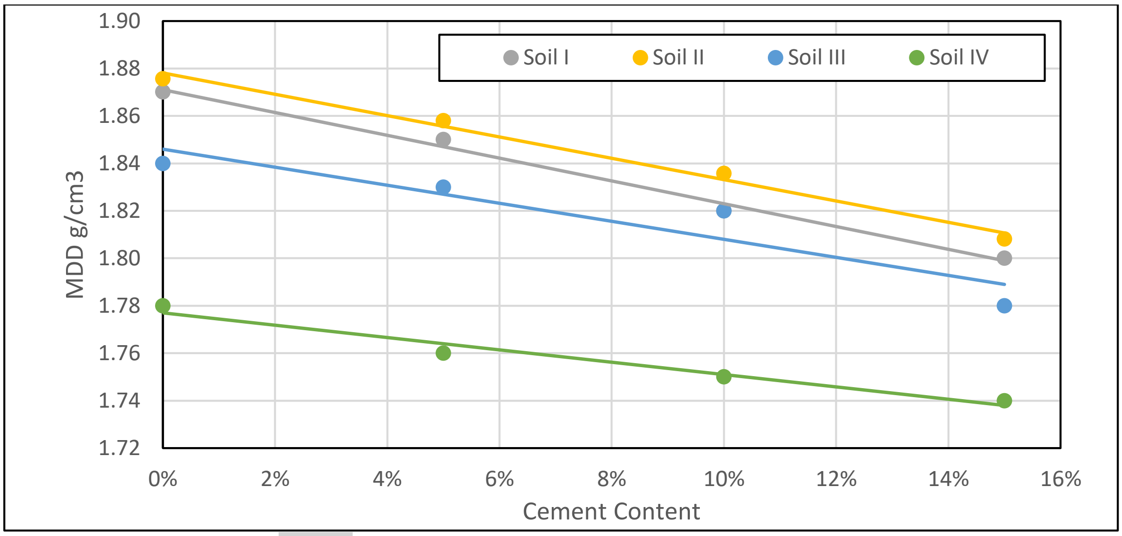

Fig. 5 The Effect of Cement on the MDD of Soil.

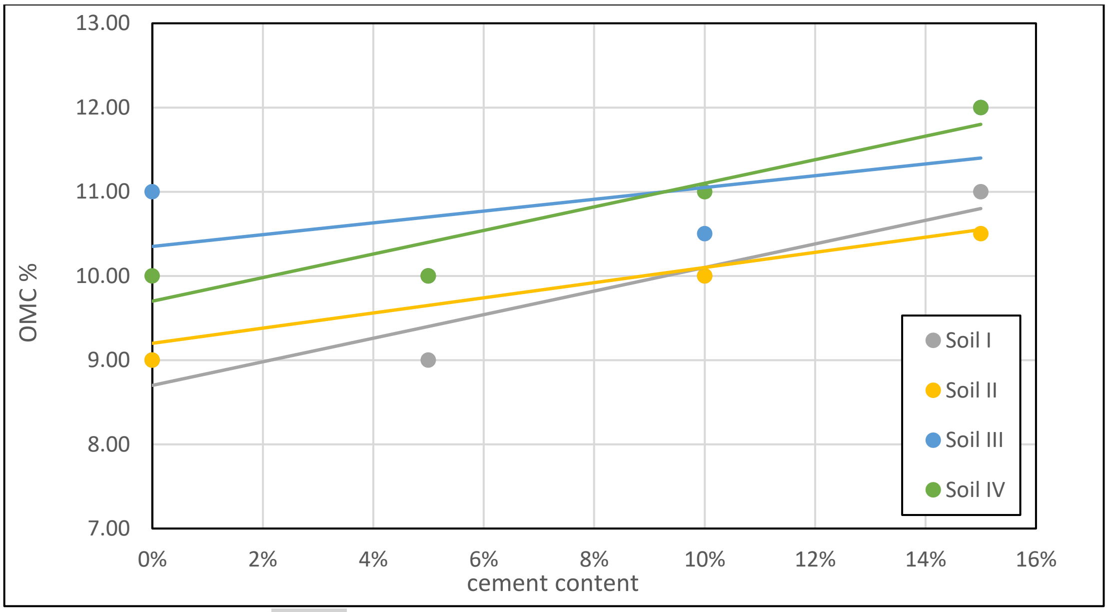

Fig. 6 The Effect of Cement on the OMC of Soil.

3.2.The Effect of Fines and Cement Content on The Unconfined Compressive Strength of Soils

The UCS tests were conducted for all the studied soils, i.e., Soil I, Soil II, Soil III, and Soil IV, containing various fines content, i.e., 30, 40, 50, and 50 %, respectively, and treated with cement. The effect of fines content on the UCS of untreated and treated soils with cement is shown in Figure 7. When the fines content was 30%, the UCS was 427 kPa. The UCS increased to 565 kPa when fines increased to 40% and then started to drop when the fines content increased. The UCS decreased to 440 and 326 kPa for soils with 50 and 60% fines content, respectively. The results showed that the optimum fines content to produce maximum UCS was 40%. Back to the results of the proctor compaction test, it was found that the maximum dry density of soils was achieved when fines content was 40%; therefore, the highest UCS of soil with 40% fines since there is a direct positive relation between the MDD and UCS [24]. The Same manner was observed for the treated soil with different cement amounts. All the treated soils achieved the maximum UCS when the fines content was 40%, as shown in Fig. 7. Fines first filled the voids available in the sand until 40%, then fines would push the sand particles far from each other, increasing the soil voids. This manner was revealed by Vu To-Anh Phan [27]. The results were considered at 28 days and clearly showed that the UCS increased as the cement content increased for all soils with different fines contents at the OMC. The UCS increase when cement was added is because of the cement hydration that produces the components responsible for gaining strength. These components are calcium silicate hydrate CSH and calcium aluminate hydrate CAH. These two components are the most significant components for soil stabilization [28]. The results also showed that the strain decreased when the cement dose increased, and the behavior of treated soil transformed from ductile to more brittle material, as shown in Fig. 8 representing the stress-strain curve for soil I as an example, and all the other soils had the same manner. The soils exhibited more strain-hardening behavior when untreated and treated with 5% of cement. The strain softening behavior was more apparent when the soils were treated with 10 and 15% cement. The increasing UCS was sharper when 10 % percent of cement was used. The average increase of UCS when cement content increased from 0 to 5%, 5 to 10%, and 10 to 15% was around 520, 690, and 285 kPa, respectively, as summarized in Fig. 9. Due to ASTM D4609-08, the UCS increase was suggested to be higher than 345 kPa to consider the treatment effective. 10% is considered the optimum cement content since it produces high-range treatment and an unconfined compressive strength of more than 1000 kPa that meets most soil stabilization applications [29]. The improvement rate of soil stabilization using cement was calculated using the equation (improving rate = (UCS stabilized soil – UCS untreated soil)/ UCS untreated soil). The rate of improvement ranged from 251 to 315 % for the four soils stabilized with 5% of cement. The UCS of the four studied soils stabilized with 10 and 15% cement increased by 580 to 852% and 626 to 960 %, respectively. On average, the UCS of soils increased by 285 % when the cement content increased from 0 to 5%, and 434% when cement increased from 5 to 10%, and 74% when cement increased from 10 to 15%, as shown in Fig. 10.

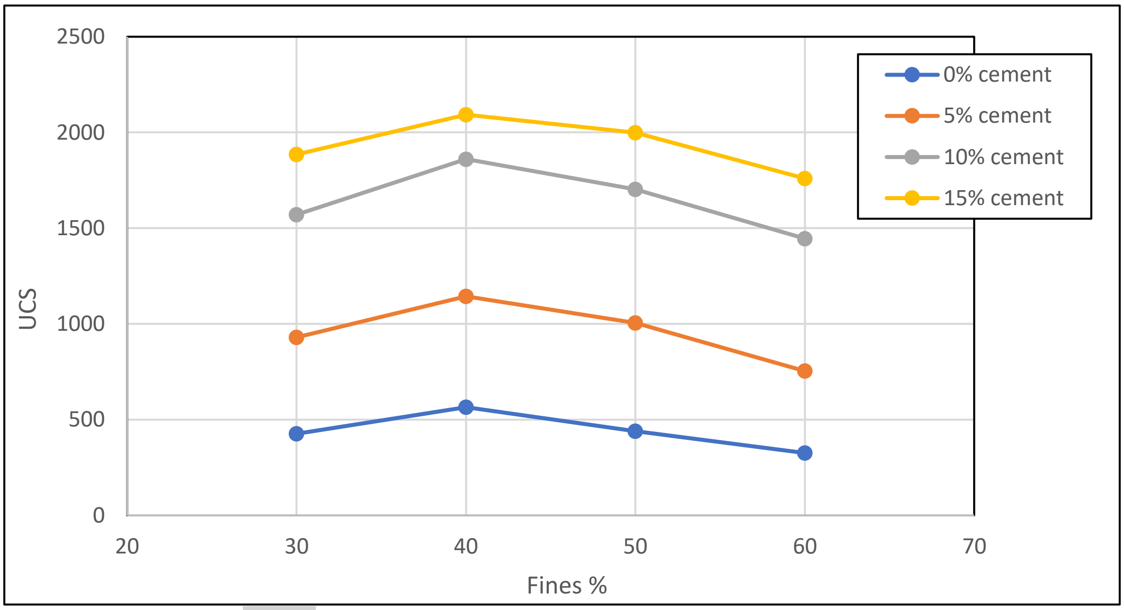

Fig. 7 The Effect of Fines Content on the UCS of Soils.

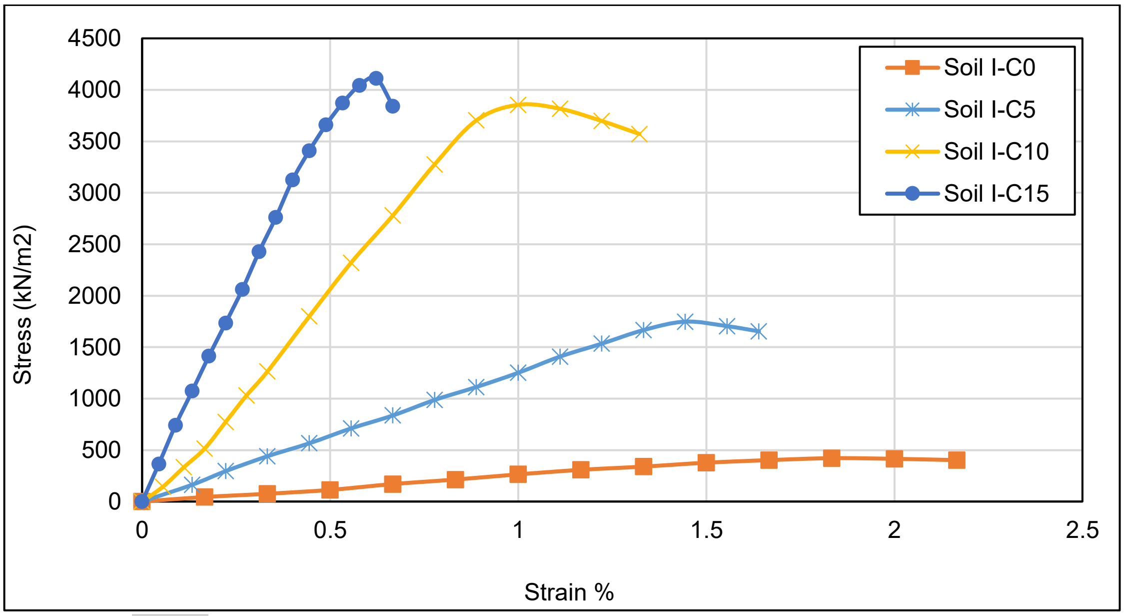

Fig. 8 Stress-Strain Relationship for Soil I for Different Cement Content.

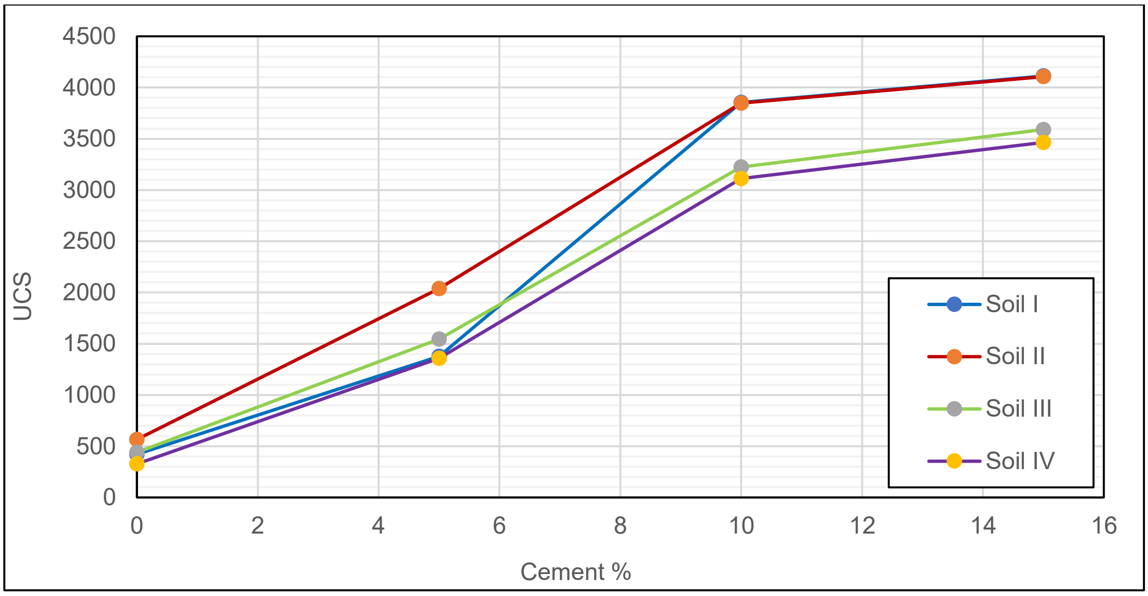

Fig. 9 The Effect of Cement on the UCS of Soils.

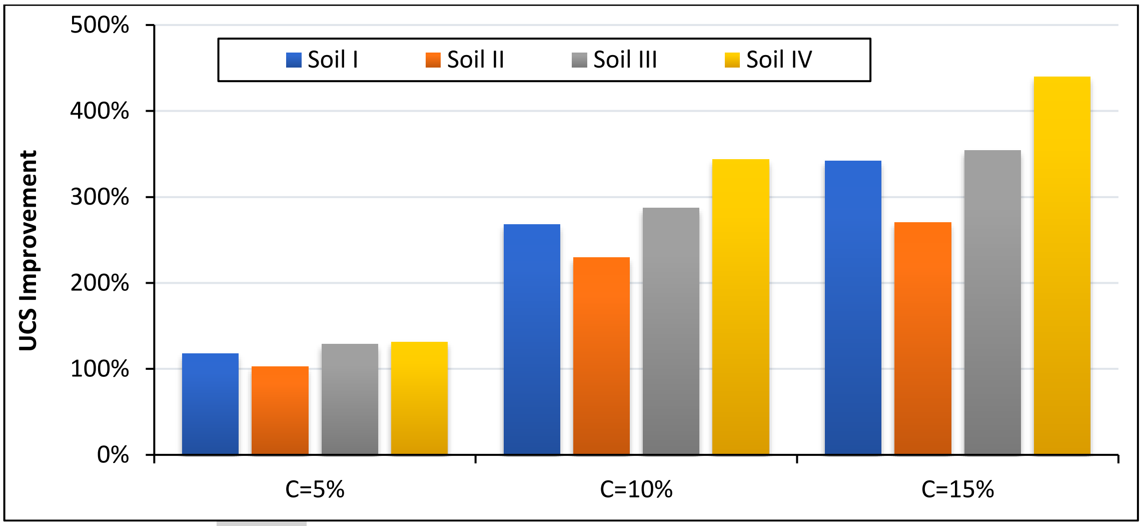

Fig. 10 UCS Improvement Rate for Cement-Stabilized Soils.

3.3.The Effect of Fines and Cement Content on The Compressibility of Soil

The plots of e-log p' curves for the untreated and treated soils were prepared and shown in Figures 11 and 12 as examples. It was hard to cure the samples for 28 days due to lack of time, for that, all samples were cured for 7 days. As mentioned earlier, the line slope beyond the yielding stress point of the e-log p' graph and the slope at the unloading phase were used to calculate the compression index (Cc) and recompression index (Cr or Cs) from the e-log p' graph respectively, as shown in Figs. 13 to 15. It can be seen that stabilizing these soils with cement improved the soil's compressibility. The consolidation settlement was reduced significantly for Soil I by 27, 51, and 97 % when 5, 10, and 15 % of cement was used, respectively, compared to the untreated soil. For Soil II, the percentages of consolidation reduction were 32, 56, and 97 % for the same previous percentages of cement. For Soil III, the consolidation was reduced by 47, 68, and 96%; for Soil IV, the reduction was 44, 68, and 96 %. Similarly, when 5, 10, and 15% of cement were used, the Cc value was reduced by 48, 73, and 97 %, respectively, compared to the untreated soil. For Soil II, the percentages of Cc reduction were 18, 80, and 97 % for the same previous percentages of cement. For Soil III, the consolidation was reduced by 55, 93, and 95%; for Soil IV, the reduction was 55, 79, and 97 %. Soil I experienced a notable reduction in the Cr value of 22%, 81%, and 100% when 5%, 10%, and 15% of cement were added, respectively, compared to the untreated soil. Similarly, for Soil II, the reductions in the Cc percentages were 45%, 94%, and 100% when the same percentages of cement were used. Soil III demonstrated consolidation reductions of 57%, 88%, and 100%, while Soil IV experienced reductions of 22%, 83%, and 92% for the corresponding percentages of cement because adding cement to soils can lead to various effects during consolidation. One such effect is the low permeability of cementitious materials, reducing water flow through the soil, slowing the consolidation settlement and enhancing consolidation traits. Another effect is forming a cementitious matrix due to cement hydration, increasing soil stiffness and strength, which can help resist the applied loads and decrease the risk of excessive deformation or settlement [30-32]. On the other hand, the graphs revealed that fines increased soil consolidation due to their small size and higher water retention capacity, leading to greater consolidation and compressibility at a slower rate [11].

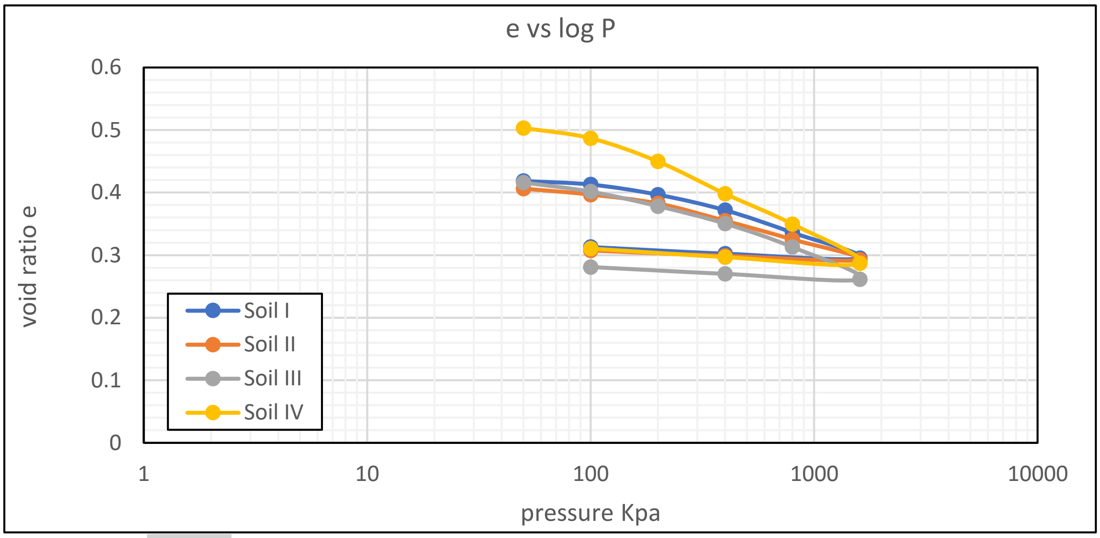

Fig. 11 Typical e-Log P Curves of the Unstabilized Soils of the Study.

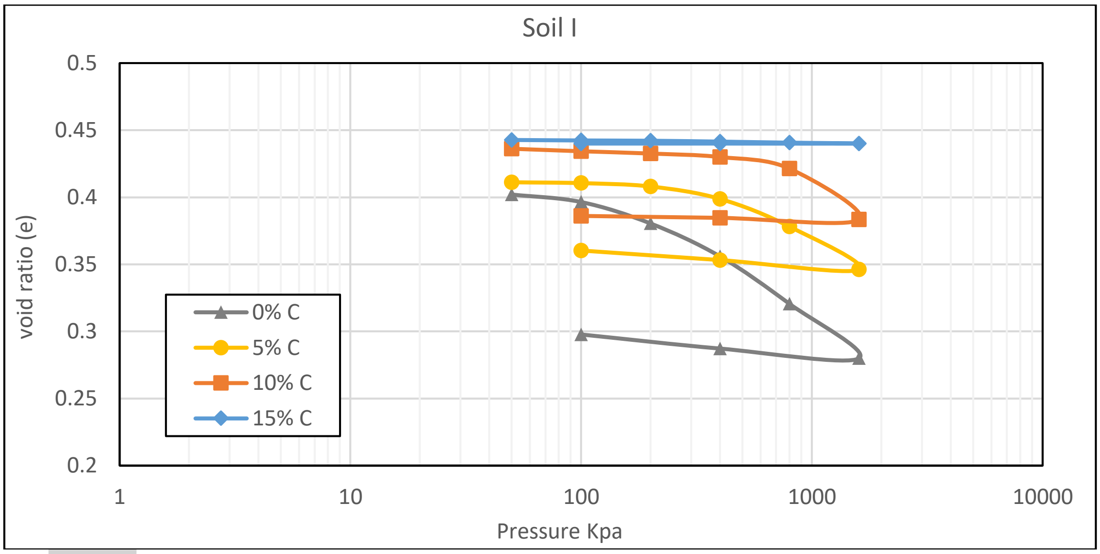

Fig. 12 Typical e-Log P Curves of Soil I Stabilized with Different Amounts of Cement.

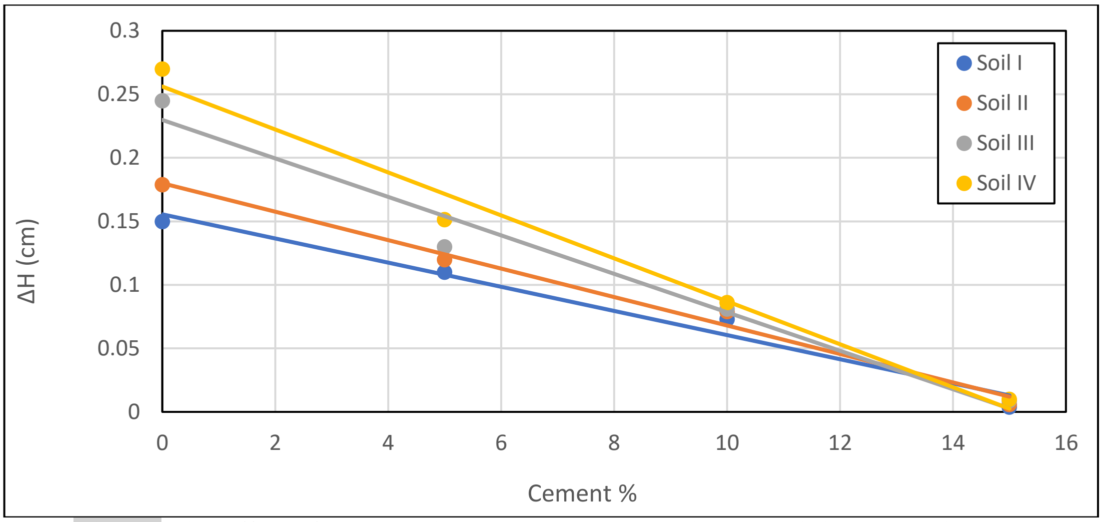

Fig. 13 The Effect of Fines and Cement Content on the Consolidation Settlement.

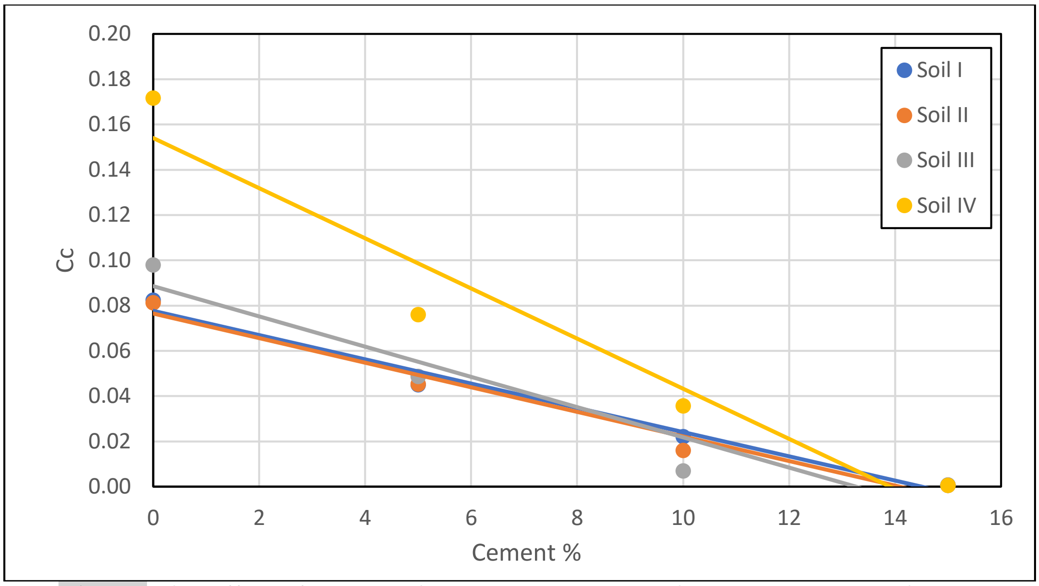

Fig. 14 The Effect of Fines and Cement Content on the Compression Index Cc.

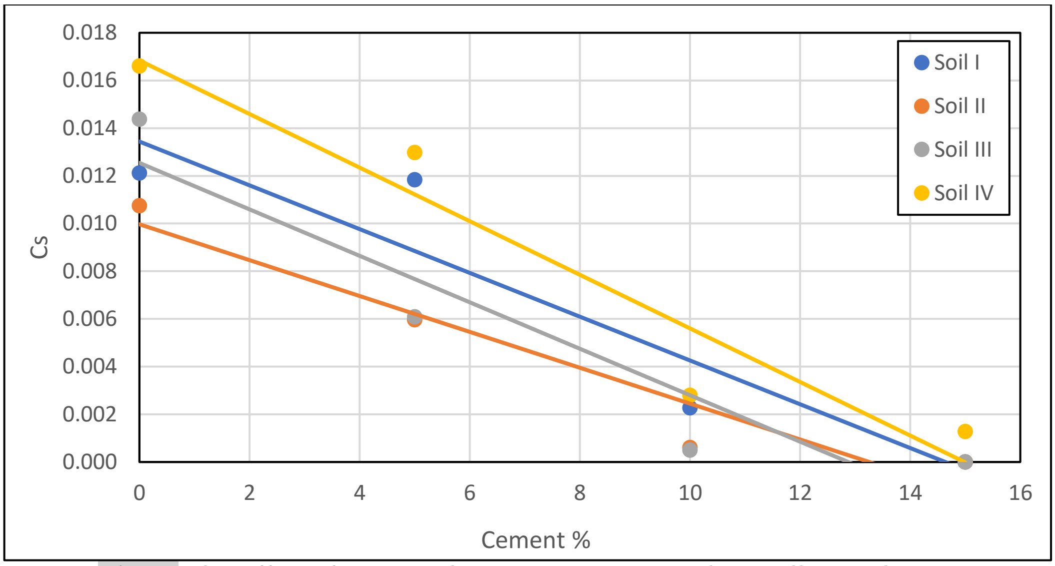

Fig.15 The Effect of Fines and Cement Content on the Swelling Index Cs.

3.4.The Effect of Fines and Cement Content on The Durability of Soil

The durability of treated sample mixtures with 10 % cement was assessed through wetting-drying tests to evaluate changes in the weight and volume of soil-cement samples. It was not possible to conduct the test for the untreated samples since they completely collapsed. The samples' weight loss and volume change are illustrated in Figs. 16 and 17. Any samples were taken out of the test if it was found that the accuracy of volume measurements was unattainable due to soil-cement loss (ASTMD559-559M, 2015). It is important to mention that the samples used to measure the weight loss were brushed, while the sample of volume change was unbrushed, as specified in (ASTMD559-559M, 2015). All treated samples survived the 12 cycles of test regarding the loss weight and volume change according to ASTMD559 since the mass and volume change was less than 10%, as shown in Fig. 18. Cement increased the bonding among soil particles, increasing the erodibility resistance [33]. The mass loss for the soils with 30, 40, 50, and 60% fines were 3.42, 3.92, 4.53, and 5.33%, respectively. On the other hand, the volume losses were 0.5, 0.9, 1.2, and 1.5% for the unbrushed samples. Figures 11 and 12 show that the mass and volume loss increased when fines content increased due to the high water retention capacity for soil with high fines content, leading to more water movement through the soil during wetting and drying.

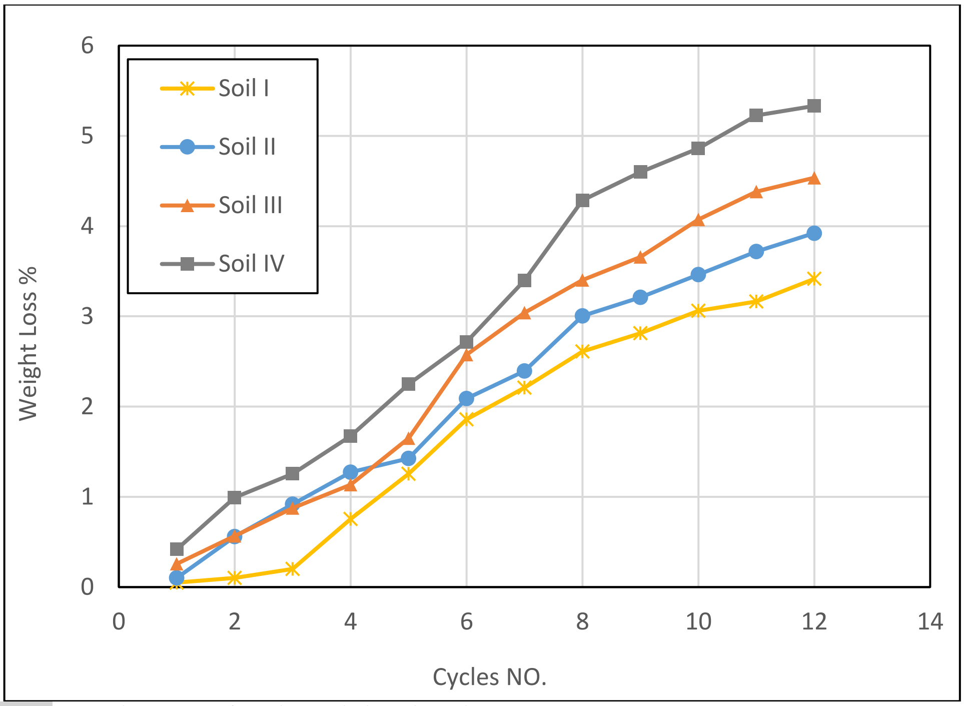

Fig. 16 Weight Loss of Soils Stabilized with 10% Cement During Wetting-Drying Cycles.

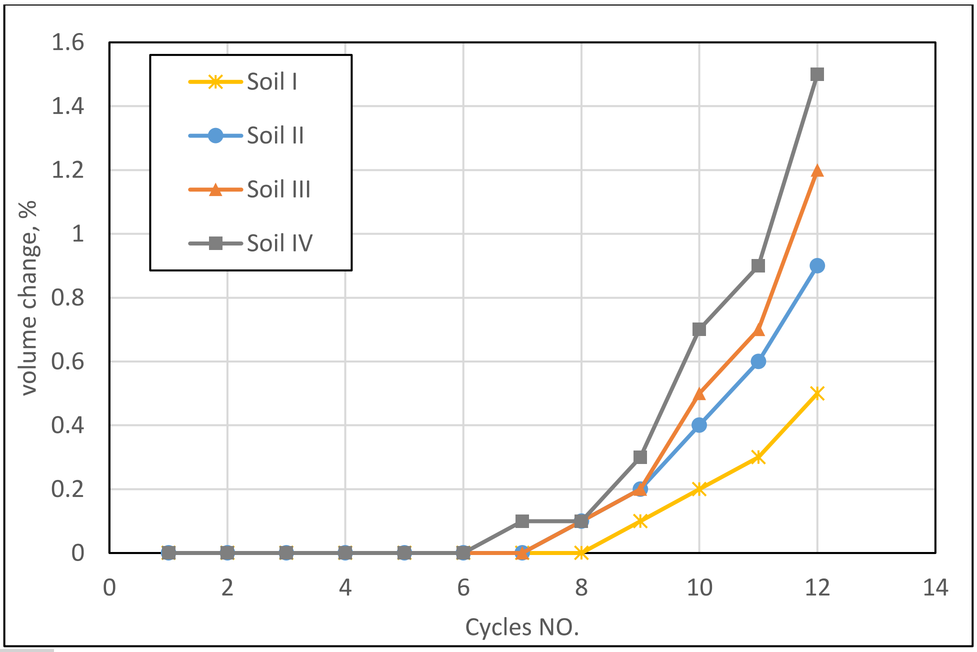

Fig. 17 Volume Loss of Soils Stabilized with 10% Cement During Wetting-Drying Cycles.

Fig. 18 Wetting-Drying Durability Test Performance for the Soils Treated with 10% Cement.

4.CONCLUSION

To reveal the effect of fines on the geotechnical properties of cement-stabilized sandy soils, a series of laboratory tests were conducted, i.e., proctor compaction, unconfined compressive, consolidation, and durability tests, in addition to the main physical tests. Four fines contents were considered, i.e., 30, 40, 50, and 60 %, and four cement contents: 0, 5, 10, and 15 percent. The main conclusions are:

1- The optimum percentage of fines that produce a maximum dry density of untreated and cemented soils was 40 % since the modification of MDD was 8, 7.4, 6.1, and 4.5% for untreated and treated soils with 5, 10, and 15% of cement, respectively.

2- The untreated soils had higher MDD than those treated with cement. The MDD values were reduced by 3.1% for Soils I, II, and III and 1.7% for Soil IV. The OMC increased slightly from about 9% to 11%, as an average for all soils.

3- The effect of fines on the UCS of untreated and cement-treated soils is similar to the MDD since 40% of fines exhibited the maximum UCS of all soils. The untreated soils UCSs were 427, 565, 440, and 326 kPa for soils with 30, 40, 50, and 50% of fines, respectively. The same manner was observed for cement-treated soils, and they achieved the maximum UCS when the fines content was 40%.

4- The UCS increased as the cement content increased for all soils with different fines contents at the OMC. The increment percentage in UCS was high when 10 % of cement was used. The values of UCS increment for Soil I when cement content increased from 0 to 5%, 5 to 10%, and 10 to 15% were around 2.27, 5.88, and 0.61, respectively. The same manner for all soils was observed. For that, 10% is considered the optimum content of cement since it produced a high range of treatments and an unconfined compressive strength of more than 1000 kPa that meets most of the soil stabilization applications.

5- The consolidation settlement was significantly reduced for Soil I by 27, 51, and 97 % when 5, 10, and 15 % of cement were used, respectively, compared to the untreated soil. For Soil II, the consolidation percentages reduction were 32, 56, and 97 % for the same previous percentages of cement. For Soil III, the consolidation was reduced by 47, 68, and 96%; for Soil IV, the reduction was 44, 68, and 96 %.

6- Fines increase the value of consolidation, Cc, and Cr for all untreated and treated soils. For untreated soil, the value of consolidation increased from 0.15 cm when the fines percentage was 30% to 0.179, 0.245, and 0.27 cm when fines increased to 40, 50, and 60 %. The consolidation values for soils with 30, 40, 50, and 60% of fines were 0.11, 0.12, 0.13, and 0.15, respectively, for soil treated with 5% cement. The same trend was for soils treated with 10 and 15% cement.

7- The mass and volume losses increased with fines content. The mass losses for the soils with 30, 40, 50, and 60% fines were 3.42, 3.92, 4.53, and 5.33%, respectively, and the volume losses were 0.5, 0.9, 1.2, and 1.5% for soils treated with 10% cement.

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