

IMPROVING THE SHEAR STRENGTH AND COMPRESSIBILITY OF SANDY SOIL BY UTILIZING CALCINED SHALE AND CEMENT

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Abstract

Sandy soil is one of the problematic soils due to the uniform distribution of the particles and the rounded shape of particles. These properties of soils lead to low shear strength, high compressibility, high collapsibility potential, and hard compaction. For that, Soil stabilization is mandatory for these kinds of soils. Calcium-based stabilizers have been used widely to stabilize these kinds of soils. Despite that, these materials have some challenges regarding environmental matter and possess numerous shortcomings, leading to the exploration of more effective stabilizers. Calcined shale has been used for concrete modification as a supplementary cementitious materials SCMs but never been used for soil stabilization. This study uses calcined shale as a partial replacement for cement to stabilize sandy soil. This research consists of two parts; the first part evaluates the optimum percentage of cement to stabilize the sandy soil used in this study. The second part is determining the optimum amount of calcined shale used to partially replace cement. The results revealed that 10% is the optimum dose of cement and 30% of CS is the best percentage to partially replace cement. 10% of cement reduced the consolidation by 98%. Using 30% of calcined shale as a partial replacement for cement increased the consolidation by 29% at a curing time of 7 days and reduced it by 9.2% when cured for 28 days.

Keywords:

Consolidation;
SEM;
Sand;
Calcined Shale;
UCS.

1 Introduction

Sandy soils exhibit significant issues and challenges, such as high compressibility, low shear strength, and low bearing strength. Soil stabilization is needed to modify some of the soil properties. Calcium-based stabilizers, especially cement, have been utilized widely to improve and stabilize different types of soils successfully [1-10]. Even though cement improves the geotechnical properties of soils, it still has issues and challenges, such as high doses of more than 3% can alter the soil behavior from ductile to a more brittle material [11]. Utilizing cement for soil stabilization is another issue since it is considered a major source of energy consumption and CO₂ emissions. The manufacture of cement produces around 1 ton of carbon dioxide per 1 ton of cement production. This represents around 7% of global carbon dioxide emissions [12]. Cement production also contributes to the greenhouse effect by producing nitrogen oxides [13]. Cement is also a more costly material than other stabilizers, such as lime, fly ash, and supplementary cementitious materials [14]. For these reasons, extensive studies are required to eliminate or reduce the dependence on cement and explore using more sustainable and environmentally friendly stabilizers. The main goal of the future is to use alternative stabilizers as a partial replacement for calcium-based binders and achieve comparable or better performance on the geotechnical properties of the stabilized soils. The Future orientation should be toward utilizing Supplementary cementitious materials for soil stabilization. Examples of these materials are metakaolin, calcined clay, zeolite, calcined shale, and natural pozzolanic [15-23]. Generally, supplementary cementitious materials have plenty of Al₂O₃ and SiO₂, which play a noteworthy role in improving the

properties of concrete and cement-treated soils. These two components react with the calcium hydroxide that is produced during the cement hydration to form Calcium Silicate Hydrate and Calcium Aluminum Hydrate. CAH and CSH are in the form of a gel that bonds soil particles together and increases the strength of the stabilized soil [24]. This improves the compressive strength and compressibility of treated soils [22]. Up to the present time, calcined shale has been used to improve the properties and modify the durability of concrete [25-27]. In this study, cement is replaced partially with calcined shale for sandy soil stabilization to reduce CO₂ emissions and energy consumption from cement production. The second goal is to improve the UCS and compressibility of the sandy soil. An extensive testing program was conducted to reveal the use of the CS along with cement for soil stabilization. The laboratory tests conducted in this study are compaction, UCS, consolidation, and Scanning Electron Microscopy SEM. The results showed a significant improvement in the UCS and compressibility of the stabilized soil. As a result, both cement and the CS can be used together to improve the compressibility and UCS of sandy soil.

2 Materials

The soil of this study consisted of 60% sand and 40% fine soil particles. The geotechnical properties of this soil are presented in Table 1. The grain size distribution of the soil used in this study is presented in Fig. 1. The chemical compositions of the cement calcined shale utilized in this study are presented in Table 2. Calcined shale is used with four different percentages: 10, 30, 50, and 70%, as a partial replacement of cement. Pozzolite possesses a nearby source of naturally calcined shale, which is a sedimentary rock formed from clay particles deposited in tranquil, muddy water. The rock's tan color and layered structure have naturally been exposed to heating from the underground heat source, Fig. 2. Cement was added to the untreated soil with three different percentages, which are 5, 10, and 15%, by the total dry weight of the soil.

Table 1: The geotechnical properties of the sand soil

Property	Standard	Studied Sample
Passing Sieve #4	ASTM D422	100
Passing Sieve #200		40
Average diameter D50		0.18
Clay fraction %	ASTM D422	11.84
Silt %	ASTM D422	28.16
Liquid limit LL [%]	ASTM D4318	41
Plastic limit PL [%]		NP
Specific gravity SG	ASTM D854	2.66
Unified Soil Classification System USCS	ASTM D2487	SM
Maximum Dry Density MDD [gm/cm ³]	ASTM D698	1.88
Optimum Moisture Content OMC [%]		9.0
Unconfined compressive strength UCS (kPa)	ASTM D2166	565

Table 2: The chemical Composition of Cement and calcined shale used in this study

Chemical Composition	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃	Na ₂ O	MgO	MnO	others
Cement	3.98	18.6	0.7	62.01	-	3.58	3.73	5.8		1.6
Calcined Shale	14.23	66.32	2.61	5.23	1.78	3.89	0.36	1.62	0.7	3.26

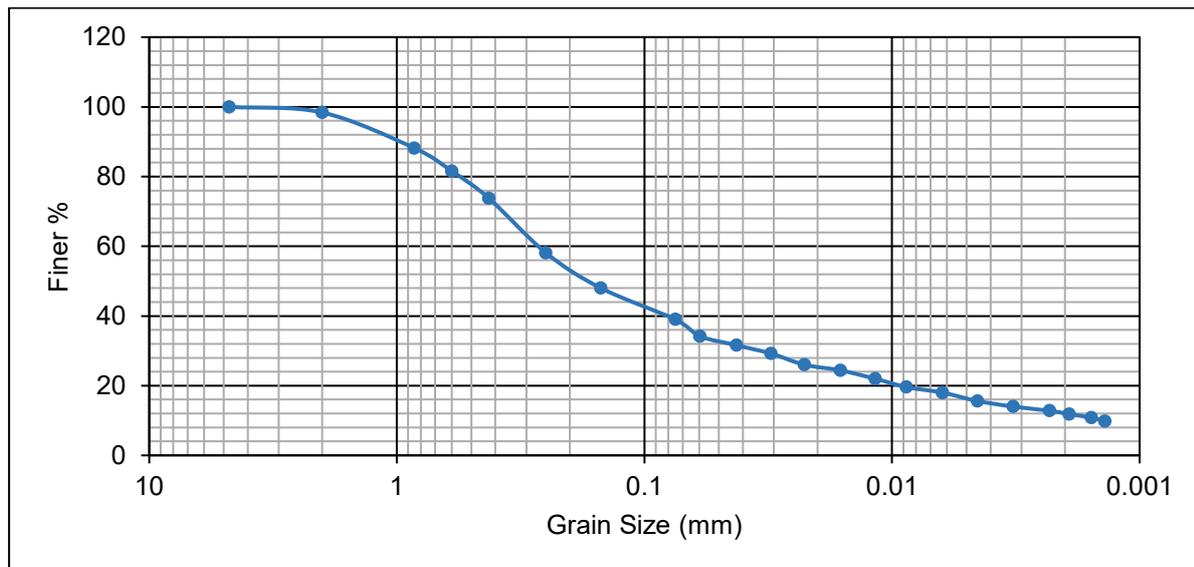


Fig. 1: Grain size distribution



Fig. 2: The calcined shale used in the study

3 Sample Preparation

Untreated standard samples, which consist of 60% sand and 40% fine-grain soil, are initially prepared. The untreated soils are mixed with three various proportions of cement: 5, 10, and 15 percent. These percentages were selected based on previous studies, which report that the commonly used range of cement for sandy soil stabilization is around 5 and 15% [28-32]. A set of unconfined compressive strength UCS is conducted to evaluate the optimum percentage of cement that produces the optimum unconfined compressive strength. Thereafter, calcined shale is utilized with four percentages, 10, 30, 50, and 70%, as a partial replacement of the optimum percentage of cement.

4 Testing Program

Geotechnical tests have been conducted, including the UCS, standard proctor compaction test, consolidation test, and microstructural tests. The experiments were conducted following the ASTM guidelines. First, the standard compaction test was conducted for the treated and untreated samples of the sand soil to attain the maximum dry density and optimum water content for all specimens. The maximum dry density (MDD) and optimum moisture content (OMC) were subsequently used in the subsequent tests. Second, UCS, consolidation test and SEM test were conducted on the treated and untreated soil samples.

5 Results and Discussion

5.1 The effect of cement and calcined shale on the compactability of sandy soil

The results of the standard compaction test showed that the MDD of the untreated soil was higher than that of the soil treated with cement, as shown in Fig. 3. The mold dimensions used in this study are 101.6 and 116.43 mm in diameter and length, respectively. The MDD decreased by 0.93%, 2.12%, and 3.6% when the cement was utilized at 5%, 10%, and 15%, respectively. The OMC increased from 9 to 10% when 5% of cement was added, and then there was no noticeable change in the OMC when 10

and 15% of cement were added. This OMC is increased due to the chemical interactions that occur when cement is added to the soil. The influx of Ca^{2+} from the cement requires more water for the cation exchange reaction [30].

When cement is partially replaced with calcined shale, the MDD decreases by 0.31, 0.86, 1.4, and 1.95% when 10, 30, 50, and 70% of calcined shale are used, respectively, as shown in Fig. 4. The OMC decreases slightly from 10% for the soil treated with cement solely to 9% for soil treated with cement and 70% of CS as partially replacing cement.

The reduction in the MDD could be attributed to the lower specific gravity of calcined shale than that of cement and soil. Replacing part of the cement with calcined shale lowers the water retention capacity, which leads to a decrease in the OMC. Flocculation and agglomeration of soil particles happen due to adding calcined shale to part of the cement, which increases the size of particles and decreases the specific surface area, which decreases the water retention capacity.

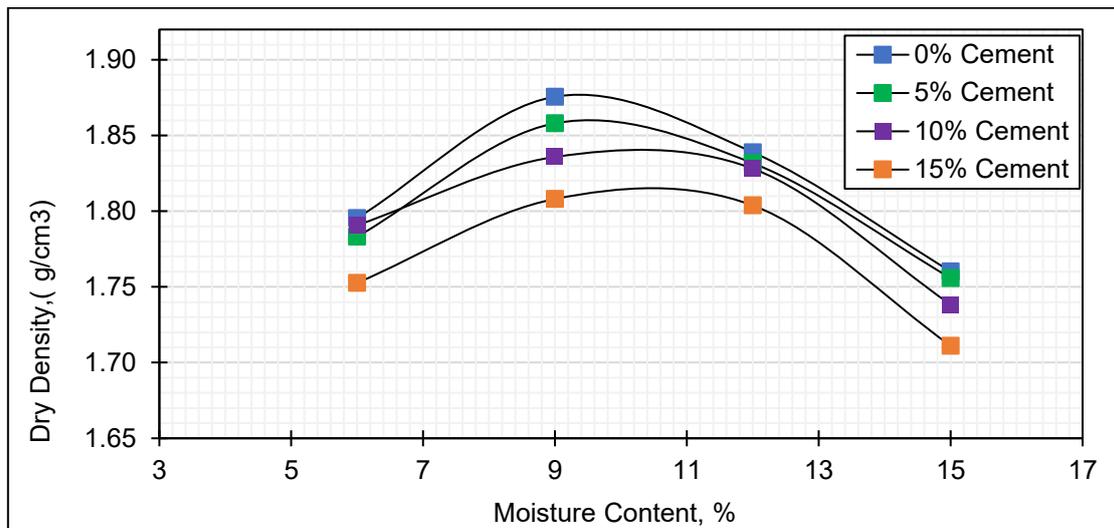


Fig. 1: The effect of cement on the MDD and OMC of sandy soil

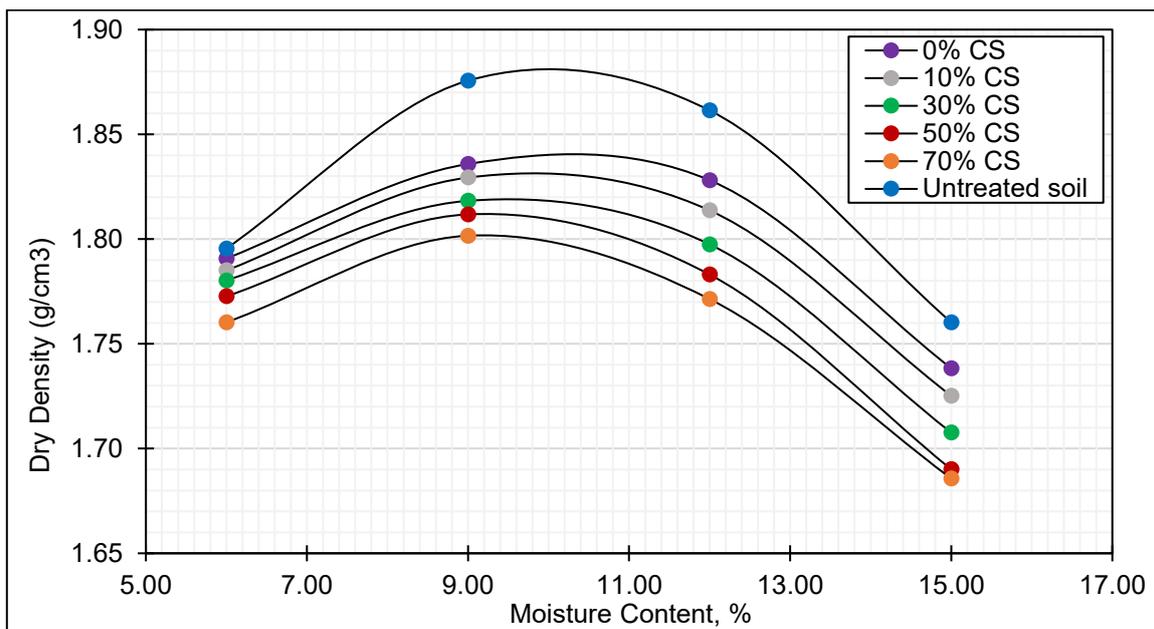


Fig. 2: The effect of CS on the MDD and OMC of sandy soil as a partial replacement of cement

5.2 The effect of cement and calcined shale on the UCS of sandy soil

Sandy soil, untreated and treated soil, was tested regarding the shear strength using the UCS test. A uniaxial loading device is used for testing with a 50 KN capacity. The device is fully automated and has a load cell and LVDT to measure the load and the deformation, as shown in Fig. 5. Shear tests could also be conducted, as conducted by [33-36], but there was lack of time to do so since all samples need curing time. The displacement rate used in this test is 1 mm/min. All samples were cured and tested after 7 and 28 days. The results revealed that adding cement increases the UCS of sandy soil when cured for 7 and 28 days, but the effect of cement at 28 days is more significant, as shown in Figs 6 and 7. Adding cement to the untreated soil with the existence of water leads to the hydration of cement and produces Calcium silicate hydrate CSH and Calcium aluminate hydrate CAH. These two components are responsible for increasing the bond between soil particles since they are in the form of gel [37]. Fig. 8 reveals that the rate of UCS improvement is the best when 10% of cement is utilized. To clarify this, increasing cement from zero to 5% leads to an increment in the UCS of 260%. Increasing the cement percentage from 5% to 10% leads to an increment of 320% and 46% if 15% is used. This gives a clear idea that the effect of cement on soil strength starts to decrease significantly when the percentage of cement is more than 10%. Due to the ASTM specification [38], chemical stabilization is effective when the UCS increment exceeds 345 kPa. Increasing the dose of cement from 10% to 15% increases the UCS by 257 kPa, which is less than 345 kPa, and therefore, it is considered ineffective. For that, 10% is considered to be the optimum percentage for sandy soil stabilization.

The second stage partially replaces the optimum cement percentage with various calcined shale percentages. At 7 days of curing, the UCS of soils treated with cement and calcined shale are less than the UCS of soils treated with cement solely. Using 10%, 30%, 50%, and 70% of calcined shale reduced the UCS of soil by 6%, 12%, 16%, and 59%, respectively. On the other hand, the UCS of cement-stabilized soil cured for 28 days is increased when calcined shale is added up to 30%, and then it starts to drop. The UCS of cemented soil increases by 8% and 18% when 10% and 30% of cement is partially replaced with CS. Utilizing calcined shale with high doses of 50 and 70% increased the UCS of cemented soil by 12 and 51%, respectively, Figs 9 and 10.

To explain this, it is significant to mention that the pozzolanic reaction between the calcium hydroxide of cement and the Silica and Alumina of calcined shale takes longer than the hydration of cement. Therefore, samples stabilized with cement and calcined shale have lower UCS when cured for 7 days than those treated with cement since the pozzolanic reactions would not have enough time to be completed entirely. Soils cured for 28 days have enough time for pozzolanic reactions to be entirely completed [15].

A balance between the amounts of silica and alumina and calcium of calcined shale and cement must be attained to achieve the optimal performance of the stabilized soil [39]. According to the chemical compositions of cement and calcined shale mentioned in Table 2, the balance is achieved when 30% of cement is partially replaced with calcined shale. For that, 30% of calcined shale represents the optimum dose of CS to be utilized for sandy soil stabilization. Some of the calcium hydroxide CaO remains unreacted if less dose of calcined shale is used. SiO₂ and Al₂O₃ remain unreacted if a lower dose of CS is used since CS is the main source of SiO₂ and Al₂O₃.



Fig. 5: The unconfined compressive strength apparatus used in this study

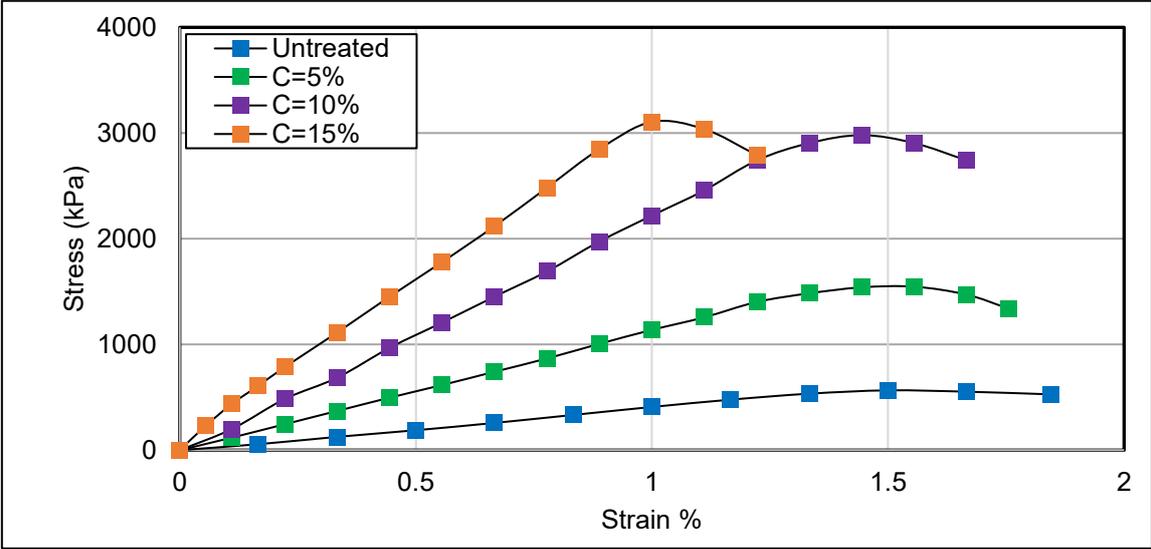


Fig. 6: Stress-strain relationship for the treated soil with different cement content at 7 days

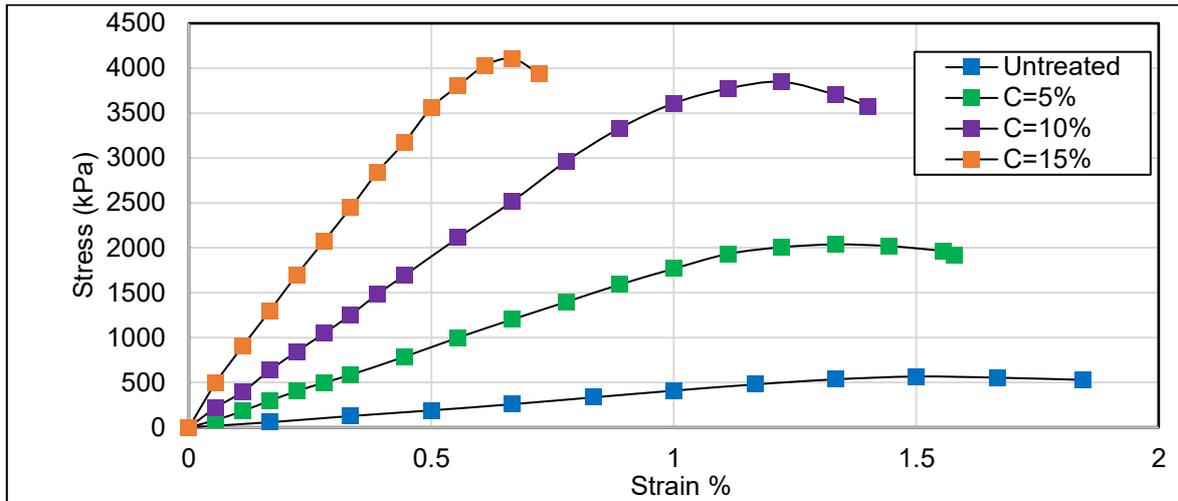


Fig. 7: Stress-strain relationship for the treated soil with different cement content at 28 days

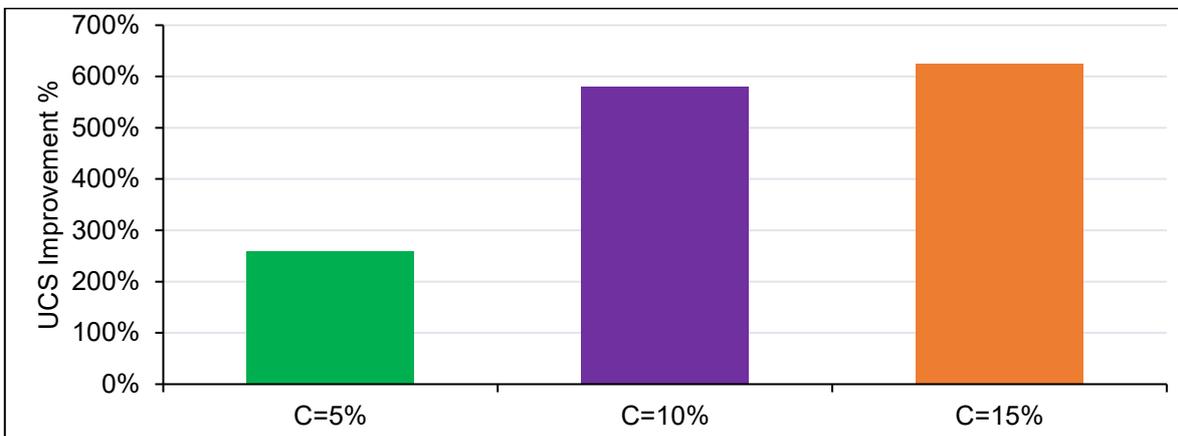


Fig. 8: UCS improvement rate for treated soil with various cement percentages at 28 days of curing

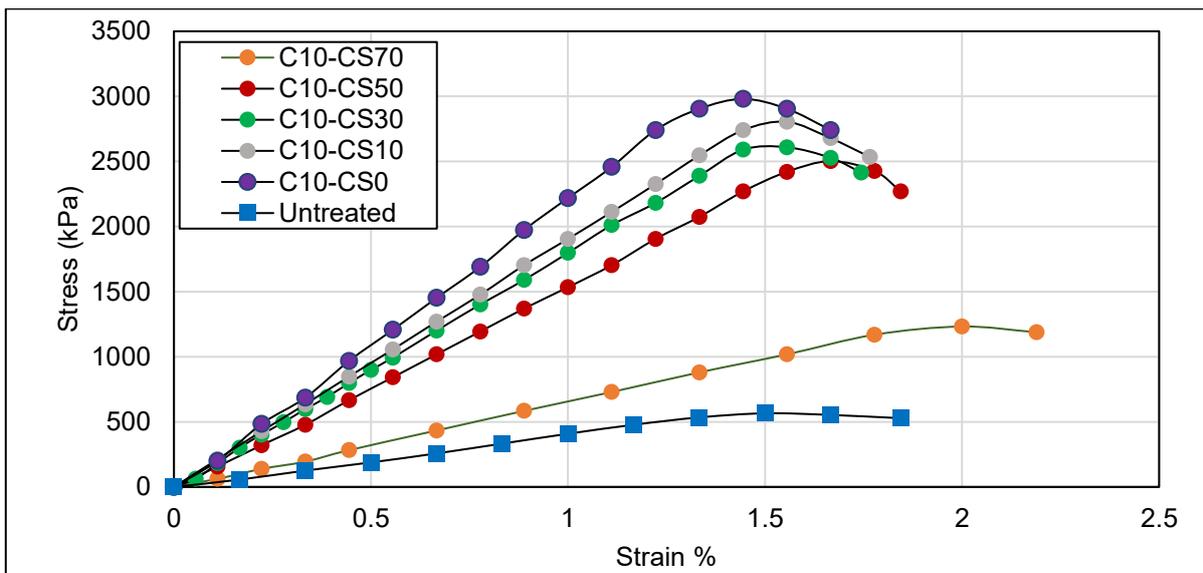


Fig. 9: Stress-strain relationship for the cemented soil stabilized with different CS percentages at 7 days

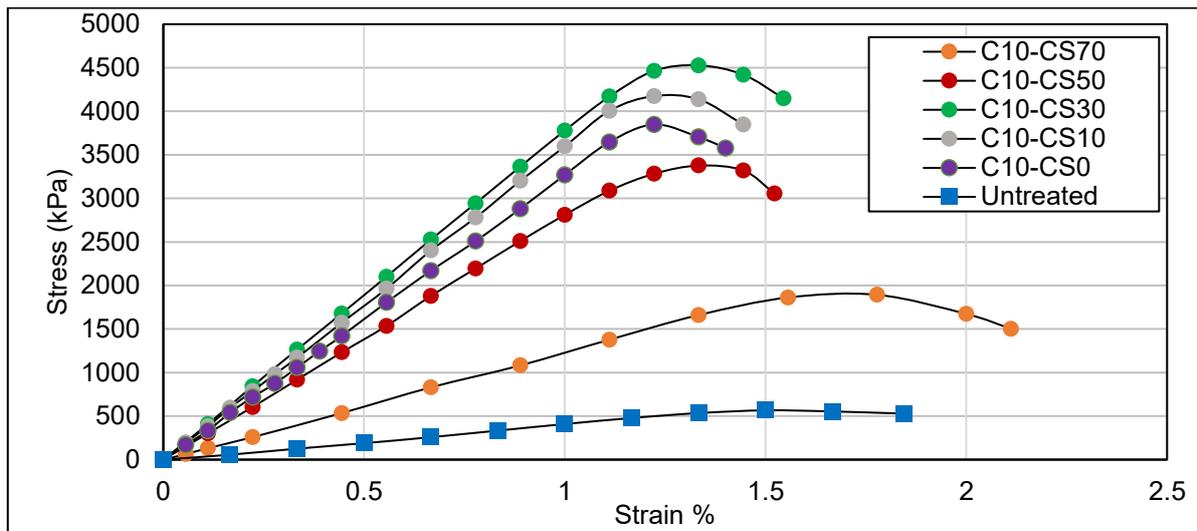


Fig. 10: Stress-strain relationship for the cemented soil stabilized with different CS percentages at 28 days

5.3 The effect of cement on the compressibility of sandy soil

The plot of e-log p' curves for the untreated and treated soil with cement doses of 5%, 10%, and 15% cured for 28 days are presented in Fig. 3. The slope of the line beyond the point of yielding stress 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. It can be seen that stabilizing the soil with cement improves its compressibility. The values of the consolidation settlement, compression, and swelling indices are presented in Table 3. The consolidation settlement was reduced significantly for the untreated soil by 33, 95, and 97 when 5%, 10%, and 15% of cement were utilized.

Similarly, when 5, 10, and 15% of cement were used, the Cc value was reduced by 50, 97, and 99 percent compared to the untreated soil. The soil experienced a notable decrease in the Cr value of 54%, 99%, and 100% when 5%, 10%, and 15% of cement were added, respectively, compared to the untreated soil. These results match the findings reported by [40-43].

The reason is that adding cement to soils can lead to various effects during consolidation. One such effect is the low permeability of cementitious materials, which reduces water flow through the soil, slowing the consolidation settlement and reducing consolidation. Another effect is forming a cementitious matrix due to cement hydration, resulting in increased soil stiffness and strength, which can help resist the applied loads and decrease the risk of excessive deformation or settlement [21, 42, 43]. This cementitious increases treated soil's strength, making it more difficult to compress and consolidate.

Table 3: Values of ΔH, Cc, and Cs of the untreated and treated soil with different amounts of cement

Soil type	ΔH (cm)	Cc	Cs or Cr
0% cement	0.179	0.0920	0.0130
5% cement	0.12	0.0453	0.0060
10% cement	0.008	0.0024	0.0001
15% cement	0.006	0.0005	0.0000

5.4 The effect of calcined shale on the compressibility of sandy soil

A series of one-dimensional consolidation tests using ELE Oedometer were conducted for treated and untreated soils following the ASTM D2435/D2435M – 11. The oedometer mold dimensions are 50 and 20 mm for diameter and height, respectively, as shown in Figure 11. The plots of e-log p' curves for the untreated soils, cement-stabilized soil, and soils treated with cement and calcined shale are shown in Fig.s 12 and 13. It can be seen that stabilizing these soils with calcined shale as a partial replacement

of cement increases the consolidation when compared to soils stabilized with cement alone. The values of the consolidation settlement, compression, and swelling indices are presented in Table 4. The percentages of consolidation increase were 25,163 and 400 percent when 10, 50, and 70 percent of cement is partially replaced with calcined shale. The consolidation is reduced when 30% of calcined shale is utilized. The consolidation value was reduced by 14% when 30% of CS was used compared to the soil stabilized with 10% cement solely.

Similarly, when 10, 50, and 70% of calcined shale were used, respectively, the C_c value increased slightly by 100, 305, and 615 percent when compared to the cement-treated soil, but it decreased by 29% when 30% of cement is partially replaced with CS. The soil experienced a notable increase in the C_r value of 300%, 914%, and 2453% when 10, 50, and 70% of cement was replaced with CS compared to the cement-treated soil, and it demonstrated a recompression index decrease by 19% when 30% of CS is added.

The reason could be the pozzolanic reaction between the alumina and silica of the CS and the CaO of cement, which produces a cementitious gel that closes the voids between soil particles. The same findings were observed in studies using natural pozzolanic such as rice husk ash, palm oil fuel ash POFA, and metakaolin [17, 44, 45] since these materials contain high amounts of SiO_2 and Al_2O_3 . The friction forces between soil particles increase due to the increment of the contact points, which increase the strength. 30 percent of calcined shale represents the optimum percentage that produces a balance among the alumina, silica, and calcium hydroxide, as mentioned earlier.

Table 4: Values of ΔH , C_c , and C_s of the untreated and treated soil with 10% cement and different amounts of calcined shale as a partial replacement of cement

Soil type	ΔH (cm)	C_c	C_s or C_r
Untreated	0.179	0.0920	0.012968
0% calcined shale	0.008	0.0024	0.00012
10% calcined shale	0.01	0.0048	0.000482
30% calcined shale	0.0069	0.0073	0.000485
50% calcined shale	0.021	0.0098	0.001221
70% calcined shale	0.04	0.0172	0.003074



Fig. 11: One-dimensional oedometer used in this study

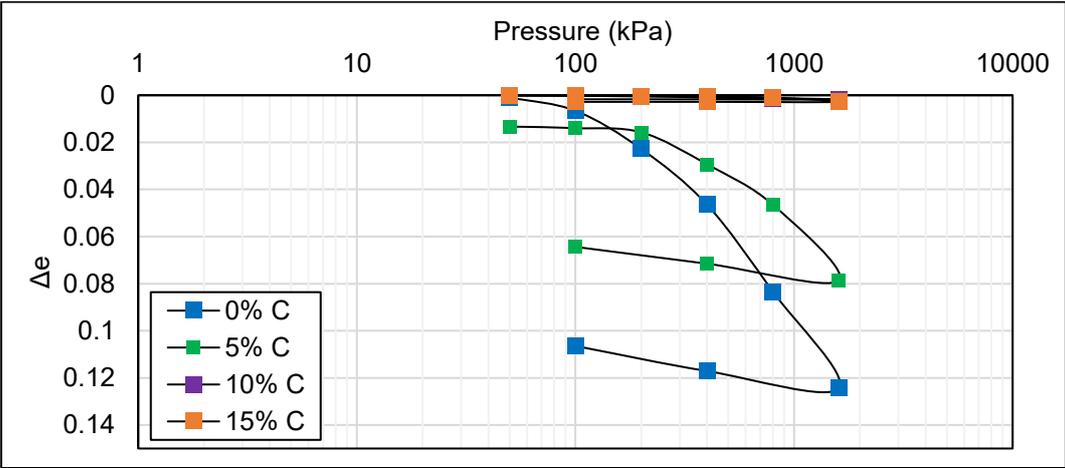


Fig. 3: Typical Δe -log P Curves of the soil stabilized with different amounts of cement

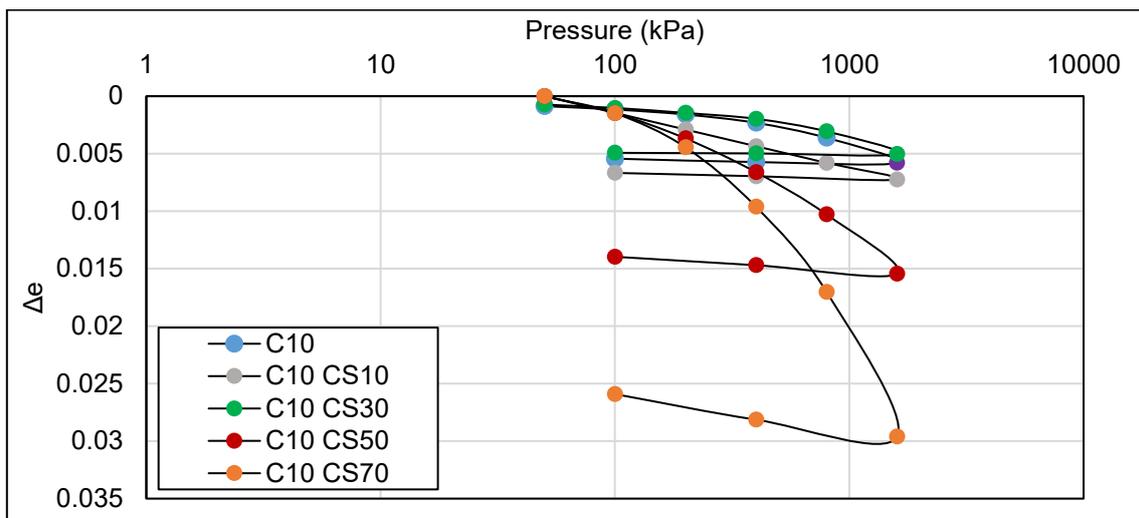


Fig. 4: Typical Δe -log P Curves of the cemented soil treated with different amounts of calcined shale as a partial replacement of cement

7 Scanning Electron Microscopy (SEM)

The influence of cement and calcined shale on sandy soil at the microstructure was illustrated using SEM test. The SEM results of treated soil with 10% cement and various percentages of calcined shale 10%, 30%, and 50% as partial replacement of cement are illustrated in Fig. 14a–d, respectively. The structure of untreated soil is changed when cement and calcined shale are added. As mentioned earlier, the main chemical compositions of the Calcine shale are SiO_2 and alumina Al_2O_3 , whereas cement mainly consists of CaO [41], as shown in Table 2.

The two chemical reactions, hydration, and pozzolanic reactions, mainly result in soil stabilization by calcium-based stabilizers such as cement [41]. Cement hydration produces calcium hydroxide, and the pozzolanic reactions follow.



Utilizing calcined shale increases the compounds CAH, CSH, and CASH due to the pozzolanic reactions between the calcium hydroxide of cement and the silica and alumina of the CS [46]. The reason is that Al_2O_3 and SiO_2 are available in an amorphous state in the calcined shale, which allows them to react effectively with the CaO of cement [47]. Moreover, the presence of cement and calcined shale modifies the size and distribution of pores in the untreated soil.

Fig. 7a presents the SEM photo of the sandy soil stabilized with 10% cement solely and shows a porous structure with the existence of CH crystals. The CH crystal needles cover a large surface of the sample. Fig. 7 b-d reveals the morphological features of the cemented soil microstructure with various percentages of calcined shale. The microstructure of the treated soil with 10% calcined shale appears to be compact and uniform in its composition. The high activity of calcine shale particles increases the pozzolanic reactions to produce more CSH gel and consequently attain a higher density than that of a sample treated with cement solely. These observations match the results of UCS and also the findings reported by [48, 49] using nano-silica to modify the cement paste.

SEM images of the soil treated with 30% CS reveal a highly compact and dense microstructure. The images show a lack of pores and non-hydrated crystals, which could explain the unconfined compression results. Fig. 7d reveals that the microstructure of cemented sand treated with 50% CS suffers from the agglomeration problem, which decreases the density of the soil and consequently affects the unconfined compressive strength. These findings confirmed that the CS is an effective stabilizer to be used for soil stabilization as a partial replacement for cement.

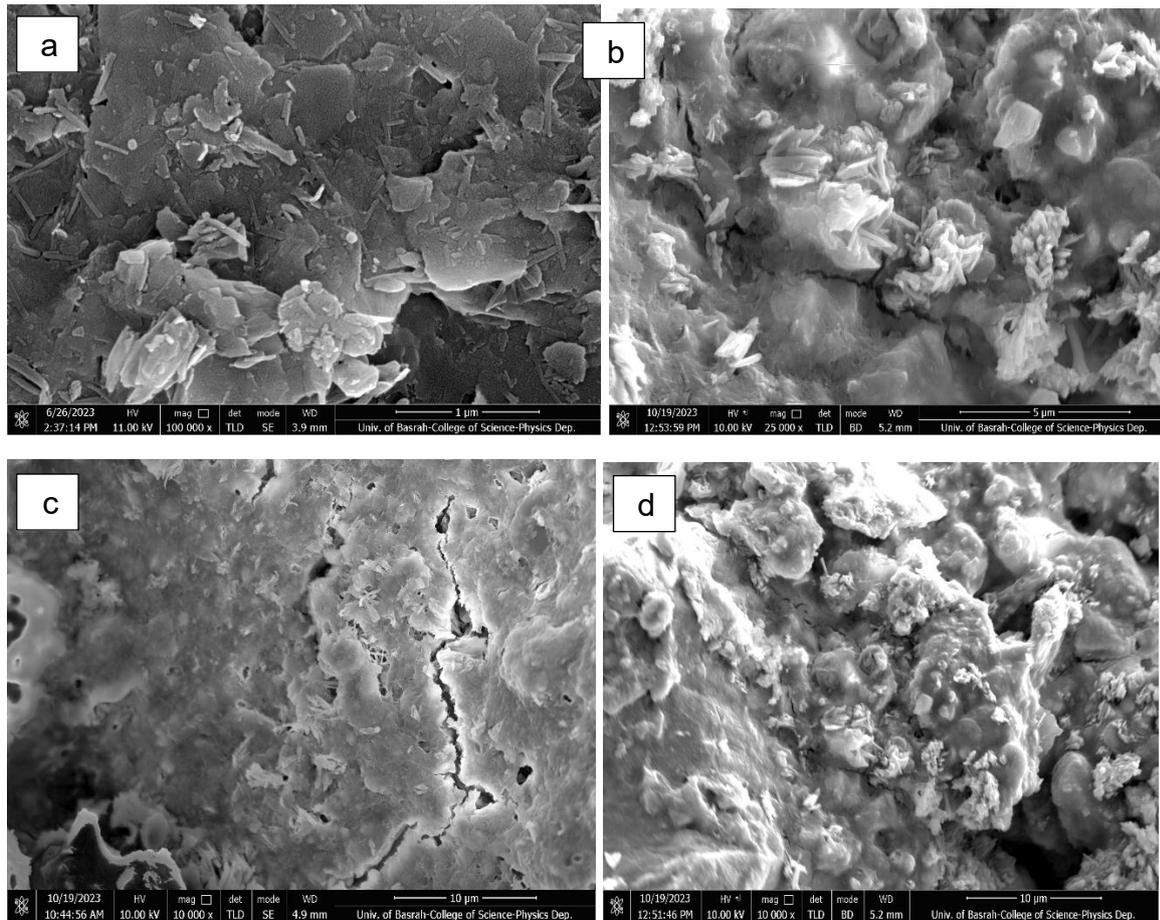


Fig. 5: SEM images of the specimen for 28 days curing: (a) specimen with 10% cement, (b) specimen containing 10% CS, (c) specimen containing 30%, (d) specimen containing 50%

7 Conclusion

A comprehensive program of tests was carried out to evaluate the effect of adding calcined shale on the geotechnical properties of cement-stabilized sandy soil. These tests included the Proctor compaction test, UCS test, one-dimensional consolidation test, and SEM test. The study used three cement percentages: 5%, 10%, and 15%, along with four different percentages of calcined shale as a partial replacement of cement: 10%, 30%, 50%, and 70%. The study reveals that adding cement to soil decreases the MDD by 0.93%, 2.12%, and 3.6% with 5%, 10%, and 15% cement, respectively, while the OMC increases from 9% to 10% with 5% cement and remains unchanged with higher percentages. Incorporating calcined shale also affects MDD, with reductions of 0.31%, 0.86%, 1.4%, and 1.95% for 10%, 30%, 50%, and 70% additions, respectively, and a slight OMC decrease to 9% when using 70% calcined shale. The UCS significantly improves at 28 days with cement additions 260%, 580%, and 625% for 5%, 10%, and 15%, respectively, while UCS decreases at 7 days when replacing cement with calcined shale 6%, 12%, 16%, and 59% for 10%, 30%, 50%, and 70%, respectively, though it increases by 18% at 28 days with up to 30% calcined shale, and decreases by 51% with 70%. Cement addition also reduces consolidation values by 33%, 95%, and 97% for 5%, 10%, and 15%, alongside reductions in compression and swelling indices. When partially replacing cement with calcined shale, consolidation values increase dramatically by 25%, 163%, and 400% for 10%, 50%, and 70%, but decrease by 14% with 30%. Furthermore, adding calcined shale changes the microstructure of the treated sandy soil, enhancing density and strength while reducing compressibility, especially at 30% calcined shale. The optimal percentages identified are 10% for cement and 30% for calcined shale for effective stabilization.

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