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# Strength and Deformability Characteristics of Cemented Clayey Sand

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ABSTRACT

Stabilization of soil using cement can increase the bearing capacity, compaction, and strength characteristics. However, limited research has been conducted on cemented clayey sand, and there is a lack of knowledge of the combined effect of clay content and cement content on the strength and deformability characteristics of mixed soil. In the present study, two soil mixtures were prepared: (1) Soil A consists of 80% sand and 20% clay, and (2) Soil B consists of 60% sand and 40% clay. The prepared mixtures were stabilized by Portland cement at target ratios of 1%, 2%, and 3% by dry weight, and they were cured for 7, 14, and 28 days. A series of unconfined compression tests were performed on the untreated and cement-treated specimens. There was a continuous increase in the unconfined compressive strength (UCS) with the increase in cement content, clay content or curing period. The deformability index rose with the growth of the clay content, but it decreased over time with increasing the curing period. Two empirical equations have been developed on the basis of the cement and clay contents to predict the UCS of cemented clayey sand at any curing time (≤ 28 days).

***Keywords:*** Clayey sand, Cement stabilization, Compaction tests, Unconfined compressive strength, Deformability index, Energy absorption capacity.

## INTRODUCTION

Inevitable construction of buildings, infrastructure, and major highways over weak soils encounters the problems of excessive total and differential settlements and inadequate bearing capacity (Mansour et al., 2015). With an annual production capacity of approximately 92 million tonnes of cement in Egypt, it is essential to use this locally accessible material to improve weak soils for current engineering projects. It has been widely documented that chemical stabilization of soil using cement can increase the bearing capacity, compaction, and strength characteristics (Yadav et al., 2018; Bayoumy et al., 2023; Mousavi & Wong, 2015). Cement offers distinct benefits compared to alternative stabilization agents. Cement stabilization is quick, does not need mellowing time, and provides a non-leaching platform. Cement can also be used to stabilize a wide range of soils (Sariosseiri et al., 2009).

Cemented soils are found naturally or prepared artificially to improve the bearing capacity (Clough et al., 1981). The characteristics of artificially cemented soils have been studied by several researchers. For example, Mitchell (1981) suggested that the friction angle of treated granular soils varies from 40° to 45°. Cohesion (in kPa) can be estimated as 0.225 times unconfined compressive strength (in kPa) plus 50 kPa. Sariosseiri and Muhunthan (2009) reported that cement treatment leads to a rise in the modulus of elasticity of tested soils. Consoli (2014) proposed a successful methodology for assessing Mohr–Coulomb failure envelope parameters based on splitting tensile strength and unconfined compressive strength of cemented sandy soils. Ashraf (2018) found that the unconfined compressive strength (UCS) in the tested samples rose with the increase of cement content up to 8%, beyond which the increase rate became slower. Ribeiro et al. (2016) stated that for every cement content, a certain optimal water content provides the highest UCS value for the tested cemented soils. Jin et al. (2018) investigated the benefits of adding a water reducer to a cement-treated soil. It was found that water reducers enhanced the maximum dry density and reduced the optimum water content of cement-treated soils. Elzamel et al. (2023) reported that the presence of cement increases the strength and resistance of sand to the liquefaction phenomenon.

Existing studies have confirmed the positive impact of adding cement to soils. However, most of them dealt with the stabilization of either pure sand or pure clay. Limited research focused on mixed-grained soils, such as clayey or silty sand (Rohmatun et al., 2024). Hence, there is a lack of knowledge of the combined effect of the clay content and the cement content on the strength and deformability characteristics of clayey sand. The present study aims to address this research gap by conducting a series of unconfined compression tests on untreated and cement-treated clayey sand specimens. The compression stress-strain curves, unconfined compressive strength (UCS), failure strain, secant modulus of elasticity ($E_{50}$), energy absorption capacity ($E_A$), and deformability index ($I_D$) of the samples are described, taking into account the combined effect of clay content and cement content. The effect of the curing time of the cemented samples is also evaluated.

## MATERIALS AND METHODS

### Materials

Natural clean sand was collected from a place in Rashid city, Egypt. The grain size distribution curve of the used sand is shown in Figure (1), and the sand is classified as poorly graded sand (SP) according to the Unified Soil Classification (USC) system. The main geotechnical properties of the sand are illustrated in Table 1. Furthermore, the clay used in the study was the commercially available kaolin clay collected from Egyptian stone pits, grinded and packaged by the Elbasatin company. The grain size distribution curve is shown in Figure (1). The physical properties of the kaolin clay are summarized in Table 2. Based on the Unified Soil Classification (USC) system, kaolin clay was classified as clay with low plasticity (CL). All tests, performed on sand and clay, were according to the American Society of Testing Material Committee (ASTM) standards. Ordinary Portland cement (grade 42.5) was used for the present investigation.

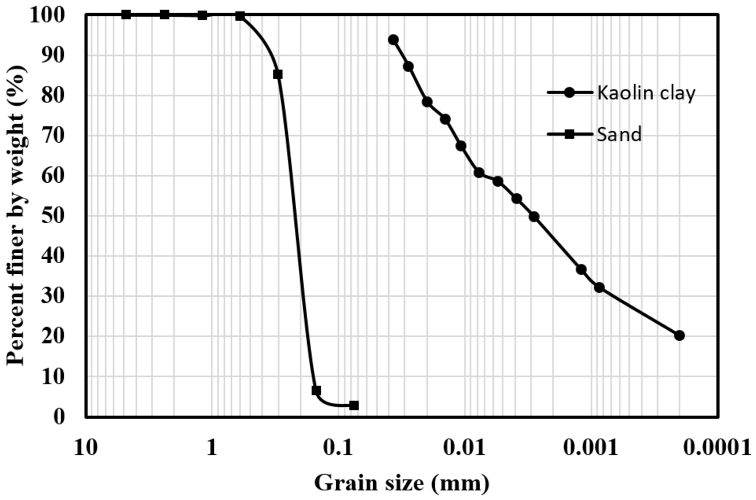


**Figure (1): Grain-size distribution of sand and clay**

**Table 1. Geotechnical properties of used sand**

| Geotechnical property | Unit | Value |
|---|---|---|
| Specific gravity, $G_s$ | - | 2.55 |
| Uniformity coefficient, $C_u$ | - | 1.61 |
| Coefficient of curvature, $C_c$ | - | 0.96 |
| Maximum dry unit weight, $\gamma_{drymax}$ | kN/m$^3$ | 16.86 |
| Minimum dry unit weight, $\gamma_{drymin}$ | kN/m$^3$ | 14.06 |
| Optimum water content, o.w.c | % | 14 |

**Table 2. Physical properties of used clay**

| Geotechnical property | Unit | Value |
|---|---|---|
| Specific gravity, $G_s$ | - | 2.7 |
| Liquid limit, L.L | % | 29 |
| Plastic limit, P.L | % | 15 |
| Plasticity Index, P.I | % | 14 |

## Sample Preparation

Initially, oven-dried sand was mixed with kaolin clay manually to prepare two homogenous soil mixtures. The first soil mixture, defined as Soil A, consists of 80% sand and 20% kaolin. The second soil mixture, defined as Soil B, consists of 60% sand and 40% kaolin. After that, modified proctor tests were conducted on each soil mixture (Soil A and Soil B) to obtain the optimum water content and the maximum dry density. The minimum dry density was also obtained for Soil A and Soil B in order to help prepare the soil mixture at the target relative density.

The amount of cement to be added was calculated according to the target content ratio based on the dry weight of the soil. The cement content was calculated according to Eq. (1):

$$C_c = \frac{W_c}{W_s} \quad (1)$$

where: $C_c$= cement content, $W_s$ = weight of dry soil mixture, and $W_c$ = weight of cement. All specimens were prepared in a medium-dense state at a relative density of 55%. The cement contents, adopted for the present study, were 1%, 2%, and 3%. The amount of water added to each specimen was to obtain the optimum water content of the cemented soil mixture. This was based on the fact that the maximum density with the most reasonable compacting effort can be achieved in engineering practice by compaction of the soil near its optimum water content. Moreover, Horpibulsuk et al. (2010) found a minimum water content needed for cement hydration of about 0.8 of the optimum water content. Table 3 presents all sets of manufactured specimens and the optimum water content corresponding to each cement content.

The specimens, tested by unconfined compression test, were prepared in 38-cm diameter by 76-cm height split moulds, which were lubricated to facilitate the extraction of the samples. The samples were then placed within plastic bags to avoid significant moisture content variations before testing. The samples were cured in a humidity room at a temperature of 22º ± 2º for 7,14, and 28 days.

## Methods

In the present research, the unconfined compression strength (UCS) was adopted as the primary indicator of the effectiveness of the inclusion of cement. In order to ensure the reliability of the results of the present study, at least three samples of some experiments were tested under the same conditions (the same cement content and the same curing time) to check for the tests' consistency. In most cases, the results were reproducible.

Unconfined compression strength (UCS) tests were performed according to (ASTM D2166) to evaluate the combined effect of clay content and cement content on the UCS of clayey sand soil. The tested specimens had a diameter of 38 cm and a height of 76 cm, and they were cured for 7,14 and 28 days. For all tests, the specimens had a relative density of 55%, and the loading was continued until specimen failure occurred or the axial strain exceeded 15%.

**Table 3. Parameters of specimens**

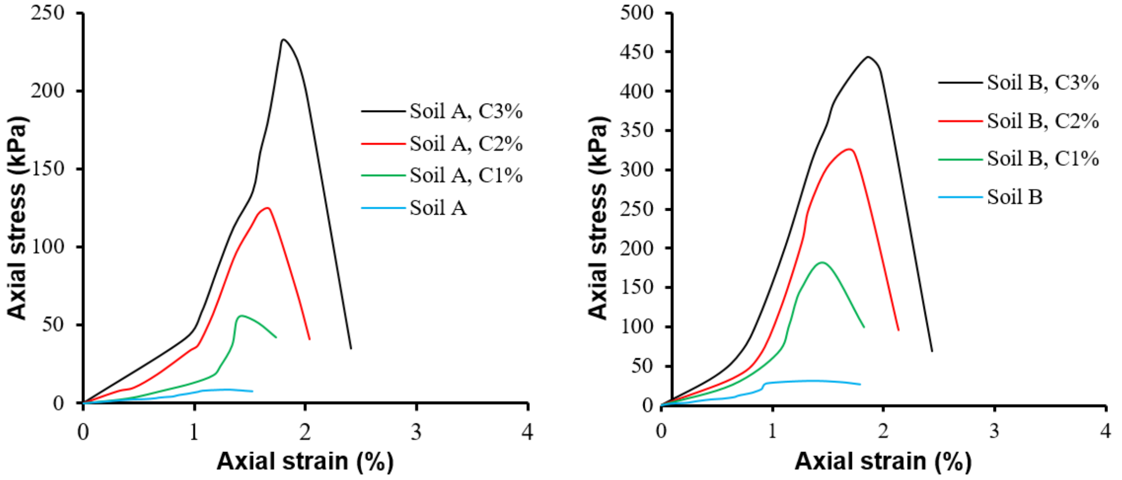
| Set number | Sample ID | $C_c$(%) | WC (%) |
|---|---|---|---|
| 1 | Pure sand | 0 | 14 |
| 2 | Soil A | 0 | 8.2 |
| 3 | Soil A, C1% | 1 | 9.5 |
| 4 | Soil A, C2% | 2 | 10.6 |
| 5 | Soil A, C3% | 3 | 11.65 |
| 6 | Soil B | 0 | 7.2 |
| 7 | Soil B, C1% | 1 | 8.4 |
| 8 | Soil B, C2% | 2 | 9.6 |
| 9 | Soil B, C3% | 3 | 10.8 |

## RESULTS AND DISCUSSION

### Stress-Strain Behaviour and Failure Mode

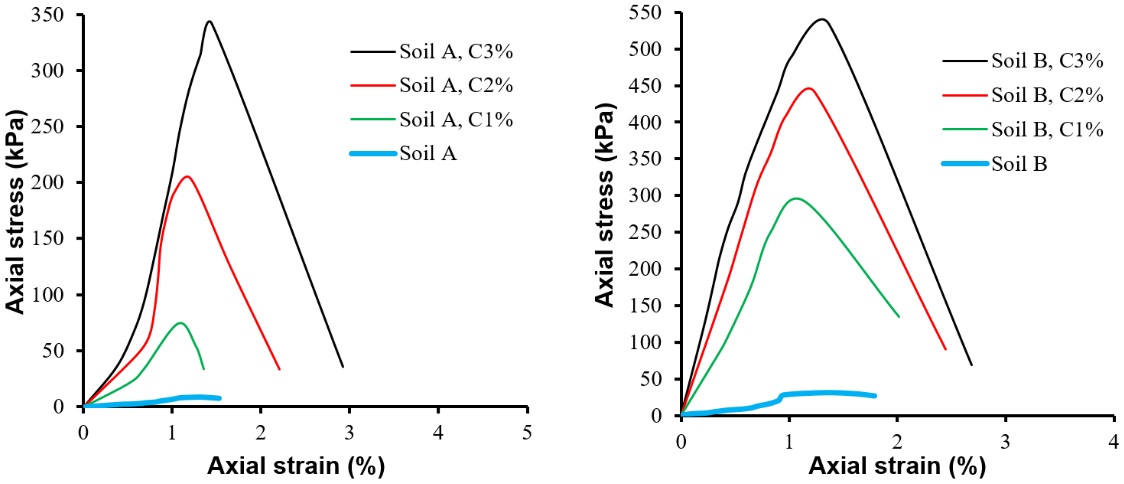
Figure (2) (a and b) shows the results of the unconfined compression tests performed on the cemented samples of Soil A and Soil B after 7 days of curing, whereas Figure (3) (a and b) presents the results obtained after 14 days of curing. Similar trends of variation of compressive stress against axial strain were observed for the samples tested after being cured for 28 days. The stress-strain curves of treated samples demonstrate a steady rise in the stress with the strain up to a peak at which a sudden brittle failure occurs. The failure was followed by a downward trend (strain softening), where there was a decline in the stress with an increase in the strain. This trend of stress-strain curves was also previously reported (Shen et al., 2021). The mode of failure of the cemented samples is presented in Figure (4). The treated samples exhibited a clear single inclined shear plane at the failure strain with no signs of bulging. As evident from Figures (2) and (3), the increase in the cement content improved the UCS. This can be attributed to the cementation effectiveness in binding the soil grains together. The chemical reaction between cement and treated soil generates cementitious gels capable of forming a network structure of a higher strength (Shen et al., 2021). Another reason can be attributed to the hydration reaction between water and cement, which consumes water and leads to a reduced moisture content. Therefore, the compressive strength of the cemented soil is improved.

The impact of the clay content on the UCS of tested samples was also examined. At the same cement content, higher values of UCS were observed for the case of Soil B compared to the case of Soil A. For instance, it can be seen from Figure (3) that the UCS was equal to 341.5 kPa and 533 kPa for the cases of Soil A and Soil B, respectively, when $C_c$=3%. This indicates that soil mixtures with higher clay contents obtain a higher UCS at the same cement content. For soil mixtures with higher sand contents, there is a higher degree of heterogeneity, which causes the failure plane to pass through the weakest zone in the sample, leading to lower UCS values (Mullins & Panayiotopoulos, 1984; Khan et al., 2014). Additionally, during the tests, sand particles may fall out from the sides of the specimens at lower clay contents, leading to a reduced cross-sectional area; hence, a reduced strength is obtained.



(a) (b)

**Figure (2): Stress-strain curves of cemented specimens tested after being cured for 7 days (a) Soil A (b) Soil B**



(a) (b)

**Figure (3): Stress-strain curves of cemented specimens tested after being cured for 14 days (a) Soil A (b) Soil B**

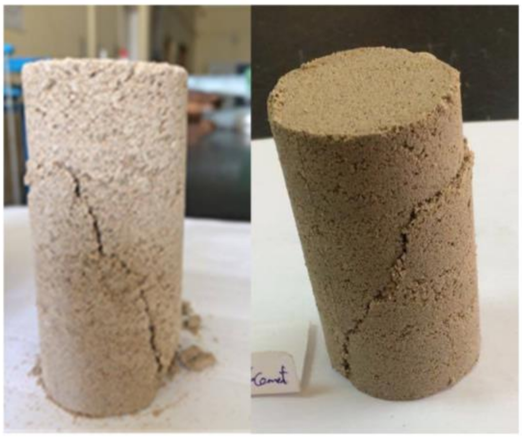
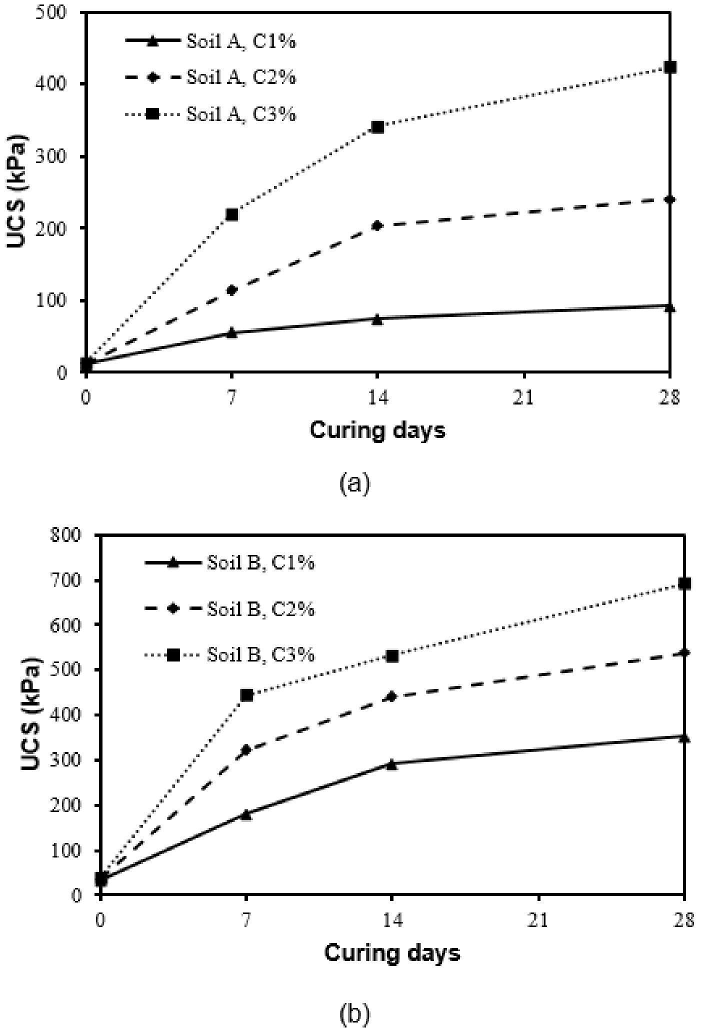


**Figure (4): Mode of failure**

### Unconfined Compressive Strength and Failure Strain

The UCS values of cemented soil specimens are plotted against different adopted cement contents for Soil A and Soil B at various curing times in Figure (5). The UCS value for each test was taken as the peak stress. It can be observed from the figure that there was a continuous increase in the UCS with the increase in cement content, which agrees with what was reported in past studies (Sariosseiri et al., 2009). For instance, at a curing time of 14 days, the UCS increased from 292.3 kPa to 533 kPa when $C_c$ increased from 1% to 3% for the case of Soil B. It was also clear that Soil B developed higher UCS values than Soil A. In addition, the curing time greatly impacts the UCS of tested samples. The highest UCS value was obtained from the samples with 3% cement content and 28 days of curing time. Figure (5) explains that increasing the curing time causes a rise in the UCS, but with a decreasing rate. For Soil B and $C_c$=3%, the UCS increased from 39.6 kPa to 656.6 kPa when the curing period increased from 0 to 28 days. The strength development in cemented soil mixtures with time is mainly attributed to the hydration process. Pozzolanic reactions continue with time, causing a gain in compressive strength. Moreover, during curing, specimens consumed the water available for the cement hydration, causing a reduction in the actual water content; hence, the reduced water content improves the compressive strength.

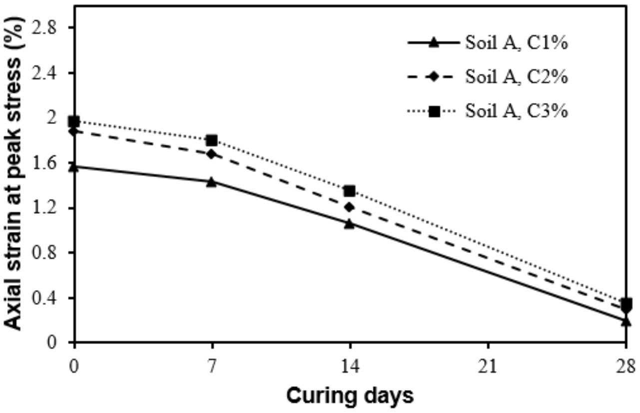


(a)

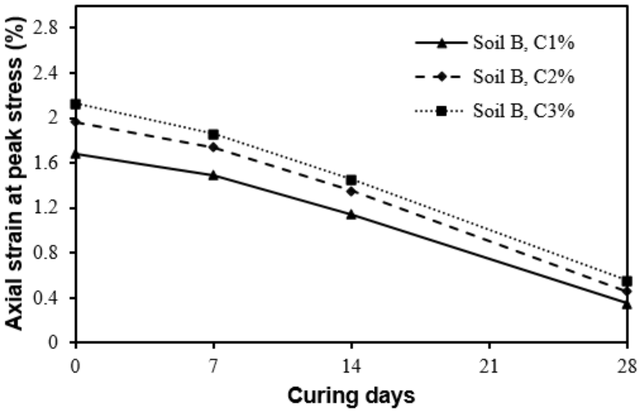
(b)

**Figure (5): Improvement of strength with curing time (a) Soil A (b) Soil B**

Figure (6) demonstrates the failure strain of the tested specimens for Soil A and Soil B at various curing times. The failure strain was taken corresponding to the peak stress. It can be seen from the figure that increasing the curing time causes a reduction in the failure strain. For example, for Soil B with 2% cement content, when the curing time increased from 7 days to 14 days, the failure strain decreased from 1.74% to 1.35%. In other words, the specimens seemed more brittle with the rise of curing time. These findings are consistent with those of (Shen et al., 2021).



(a)



(b)

**Figure (6): Reduction of failure strain with curing time (a) Soil A (b) Soil B**

The combined effect of cement and clay contents on the deformation characteristics was also assessed. For all tested specimens, the failure strain ranged from 0.2% to 2.0% and from 0.4% to 2.1% for Soil A and Soil B, respectively. For the same cement content and the same curing time, it was observed that increasing the clay content made the samples more ductile and break at a higher strain. At a curing time of 14 days and $C_c$ of 2%, Soil A broke at a failure strain of 1.2%, while Soil B broke at a failure strain of 1.4%. It was also observed that there was a slight increase in the failure strain with the increase in cement content. For instance, when $C_c$ increased from 1% to 3% for the case of Soil B, the failure strain rose from 1.2% to 1.5% at a curing time of 14 days.

### Secant Modulus of Elasticity ($E_{50}$)

The secant modulus of elasticity ($E_{50}$) was determined by calculating the slope of straight lines drawn up to 50% of the UCS in the stress-strain curves. The values of $E_{50}$ are plotted against various cement contents for Soil A and Soil B in Figure (7). While the plot was for curing times of 7 days and 14 days, a similar trend of variation of $E_{50}$ with $C_c$ at a curing time of 28 days was observed. The secant elastic modulus was dependent on both cement and clay contents. It was previously stated that the strength behaviour gets enhanced by increasing either the cement content or the clay content. Therefore, a similar variation trend of $E_{50}$ was observed here. Soil B has a higher $E_{50}$ than Soil A at the same $C_c$ and the same curing time. Moreover, at the same clay content and a curing time of 14 days, $E_{50}$ increased from 24.4 MPa to 55.5 MPa when $C_c$ increased from 1% to 3%.

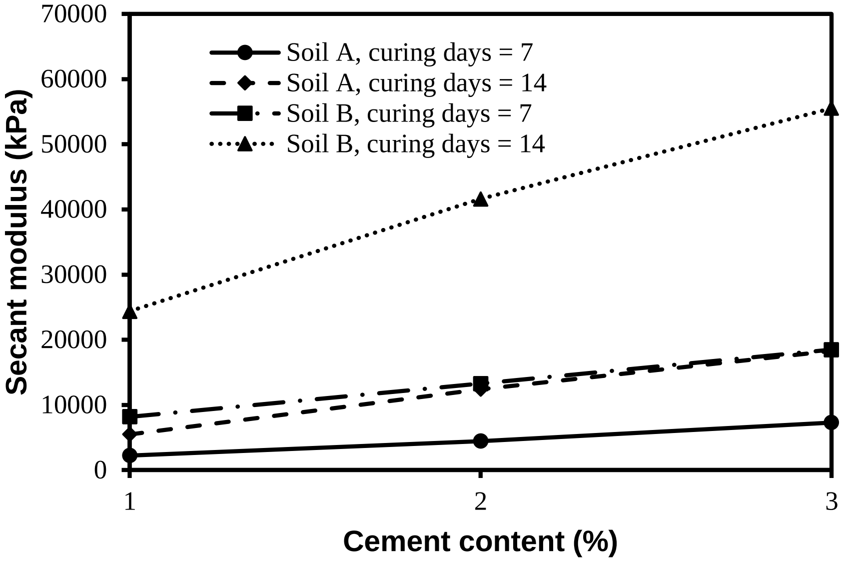


**Figure (7): Improvement of secant modulus with cement content**

Since the strength behaviour improved with the increase in the curing time due to the hydration process, $E_{50}$ was found to increase continuously over time. A higher increase rate of $E_{50}$ was observed for higher periods of curing time. The trend of increasing the elastic modulus with increasing the cement content, presented in this study, was also confirmed by Park (2011) who studied fiber-reinforced cemented sands, but his study was limited to a curing time of 7 days.

### Deformability Index ($I_D$)

The deformation behavior of cemented soil specimens was described by the deformability index:

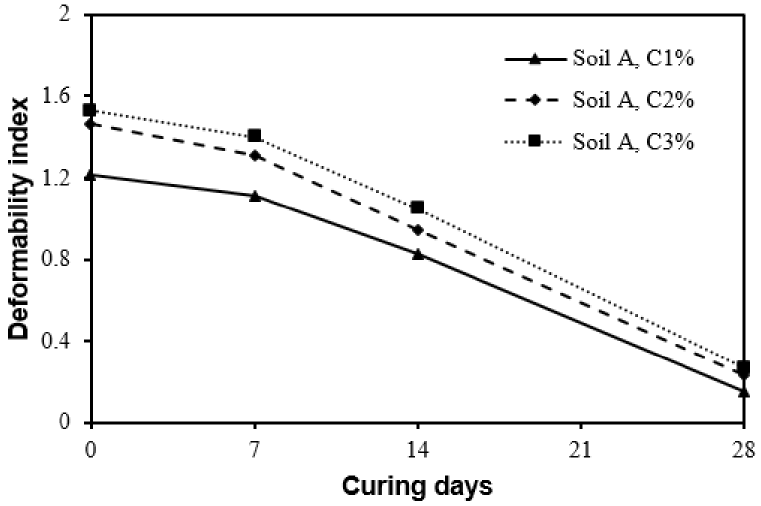
$$I_D = \frac{\Delta_{cement}}{\Delta_{no\ cement}} \quad (2)$$

where: $I_D$= deformability index; $\Delta_{cement}$ = failure strain of cemented soil; and $\Delta_{no\ cement}$ = failure strain of non-cemented soil. The deformability index is a helpful parameter, especially when the residual stress condition is not clearly observed in the stress-strain curves (Choobbasti & Kutanaei 2017; Park, 2011). The variation trend of $I_D$ is dependent on that of the failure strain of cemented samples; hence, $I_D$ can be used to evaluate the deformation behaviour. The deformability index was calculated and plotted against various curing periods for Soil A and Soil B in Figure (8). $I_D$ was found to range from 0.27 to 1.21 and from 0.41 to 1.27 for Soil A and Soil B, respectively. For the same cement content and the same curing time, higher values of $I_D$ were observed for Soil B compared to Soil A.

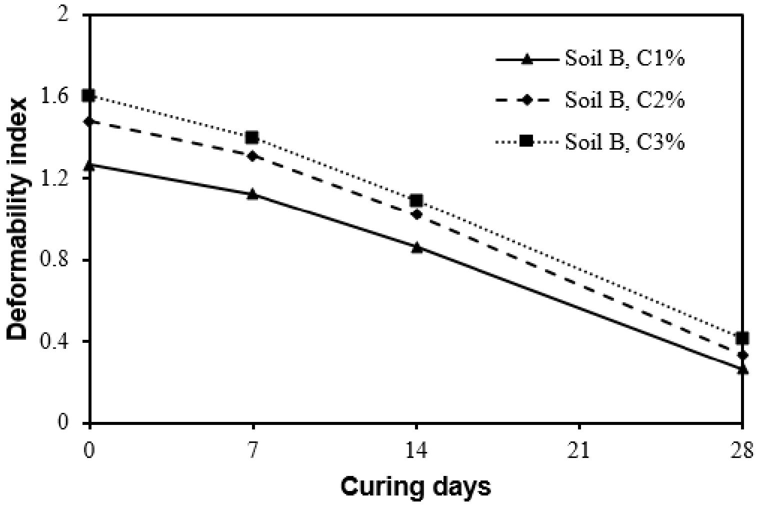
While $I_D$ increased with the increase of the cement content, it decreased over time with increasing the curing period. This can be attributed to the variation trend of the failure strain of cemented samples, which was previously discussed. Increasing the curing period improves the strength behaviour, but leads, in turn, to more brittleness and lower failure strains. On the other hand, increasing the cement content leads to increasing the water content used in preparing the specimen (taken as the OWC), which leads to the rise of both the strength and the failure strain. This is due to the higher lubrication provided by higher water contents, helping the sand particles slide relatively over each other easily; hence, more strain is generated before failure occurs.

### Energy Absorption Capacity ($E_A$)

The amount of energy needed to cause a deformation in the cemented samples is defined by the energy absorption capacity, $E_A$ can be determined by calculating the area below the stress-strain curve up to the desired axial strain. Figure (9) displays the variation of $E_A$ against the axial strain at different cement contents for Soil A and Soil B. As can be seen from the figure, Soil B has higher values of $E_A$ compared to Soil A at the same cement content and the same curing period. For instance, the energy needed to cause an axial strain of 1.2% was 3.18 $kJ/m^3$ and 0.97 $kJ/m^3$ for Soil B and Soil A, respectively, at a cement content of 2% and a curing period of 14 days. Furthermore, $E_A$ was found to increase with increasing either the cement content or the curing period. This can be attributed to the increase in the cemented samples' stiffness and the UCS by increasing the cement content or the curing time. Hence, the area below the stress-strain curves of specimens, with the highest cement content and highest curing period, was the greatest among all tested specimens. It is also obvious from the figure that the increase rate of $E_A$ with the axial strain decreased after reaching a specific axial strain. For example, the increase rate of $E_A$ started to drop at an axial strain of 2% for Soil A with a cement content of 3% and a curing period of 7 days.

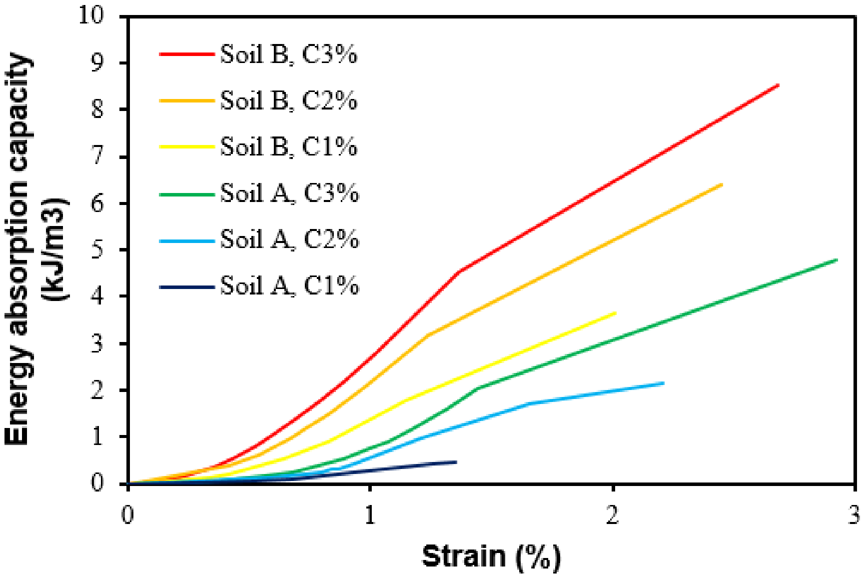


(a)



(b)

**Figure (8): Variation of deformability index with the curing period (a) Soil A (b) Soil B**



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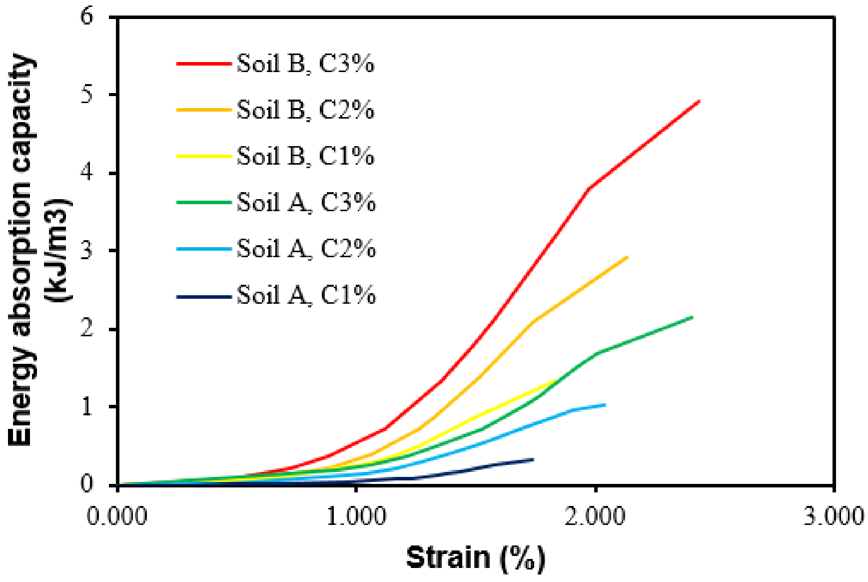

(b)

**Figure (9): Variation of energy-absorption capacity with the strain**
**(a) curing days = 14 days (b) curing days = 7 days**

**Prediction of UCS of Cemented Clayey Sand**

An empirical equation has been developed on the basis of multiple linear polynomial regression analysis to predict the UCS of cemented clayey sand at a curing time of 28 days. The model was created with the cement and clay contents as independent variables and the UCS as the dependent variable. A plot between the predicted values of UCS and the experimental values is presented in Figure (10), which shows the model's performance in terms of prediction. A good match between the observed values and the predicted values of UCS can be seen in the figure. The coefficient of determination ($R^2$) was 0.99.

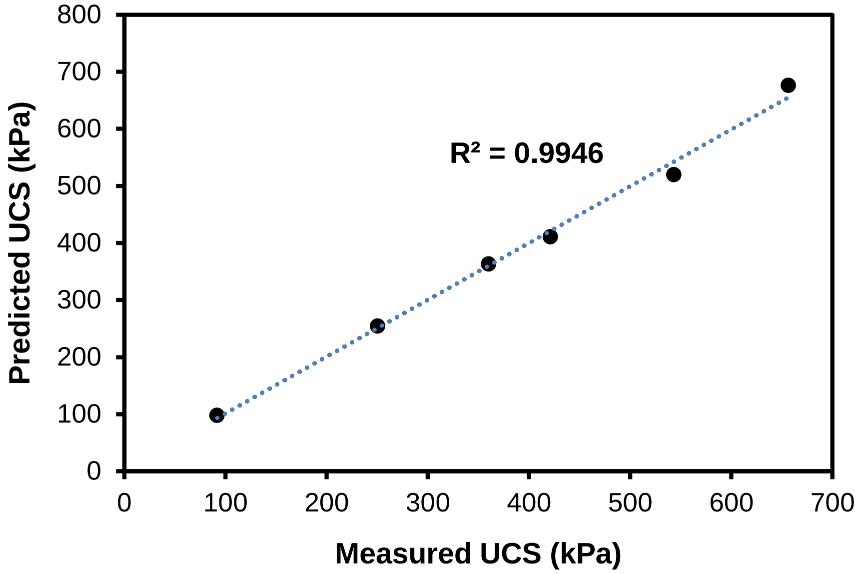

**Figure (10): Predicted *versus* measured values of UCS**

$$\mathrm{UCS} = -324.01 + 13.274 * \mathrm{Cl_c} + 156.527\,\mathrm{C_c} \qquad (3)$$

where: UCS = unconfined compressive strength (kPa); $\mathrm{Cl_c}$ = clay content (%); and $\mathrm{C_c}$ = cement content (%).

Additionally, another empirical equation was developed for predicting the UCS of cemented clayey sand at a curing time of D days. The values of UCS at different curing periods are normalized by the UCS of the same soil sample after 28 days of curing. The increase in strength over time can be written as a second-order polynomial function, as shown in Figure (11). In this way, after predicting the UCS at a curing time of 28 days using Eq. (3), the UCS can be estimated at any required curing period using Eq. (4). The coefficient of determination ($R^2$) was 0.987.

$$\frac{\mathrm{UCS\ (D)}}{\mathrm{UCS\ (28)}} = -0.0015D^2+0.0754D+0.0752 \qquad (4)$$

where: $\frac{\mathrm{UCS\ (D)}}{\mathrm{UCS\ (28)}}$ = compressive strength ratio; and D = curing time (days).

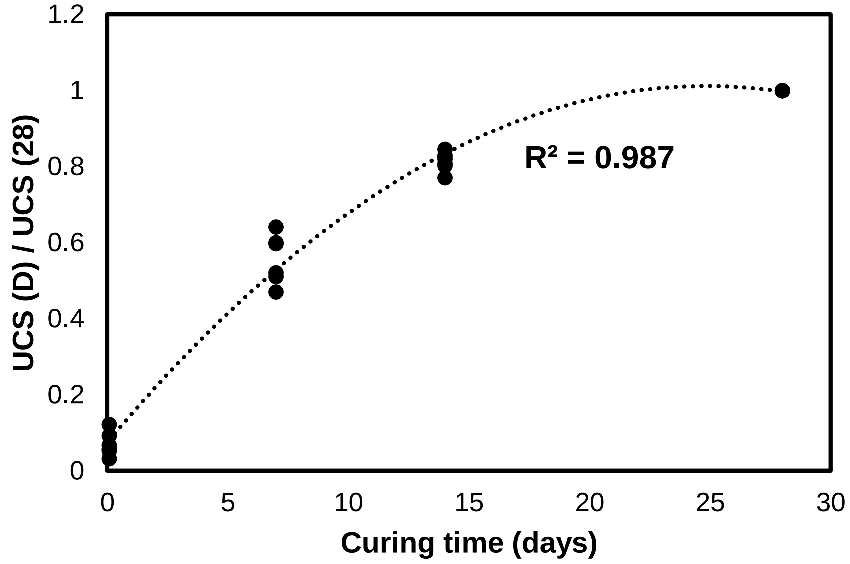

**Figure (11): Relationship between compressive strength ratio and curing time**

### Comparison with Previous Investigations

Since previous investigations on clayey sands are limited, comparisons will be held with past studies on other soil types. In the present study, the curing time resulted in the improvement of the UCS and the reduction of peak failure strain, which has been reported by several researchers (Eskisar, 2015). What was noteworthy is that there was a slight increase in the failure strain (more ductility) with the increase in cement content in the tested specimens at the same curing time. This led to the increase of $I_D$ within a narrow band of values. Several previous studies also reported cases of stability or an increase of the failure strain with increasing cement content (Park, 2011; Chen et al., 2015; Choobbasti & Kutanaei, 2017; Chandu & Rao, 2021). This may be because the cemented samples were tested at the optimum water content of each cement content. As the cement content increases, the optimum water content increases, as presented in Table 3. Increasing the water content in the sample leads to an increase in the ductility of the tested sample (Muhmed et al., 2022; Khan et al., 2014). Contrary results would have been found if a constant water content was utilized for all cemented specimens under testing; $I_D$ would have decreased with the increase of the cement content due to the reduction of the failure strain of the cemented sample, as reported in several past studies (Balasubramaniam et al., 2001; Pakbaz et al., 2012). Therefore, it can be concluded that it is advised to achieve the optimum water content in the field for engineering projects to obtain the highest possible deformability from the cemented soil.

### Limitations

Although chemical stabilization using cement has proved to be effective in improving the behaviour of soils, environmental issues have grown over time due to the high energy consumption of cement production and associated contamination rates (Ayeldeen et al., 2016; Wang et al., 2020; Elroul et al., 2023). Several industrial waste materials, such as fly ash, silica fume and cement kiln dust, can be used as partial or complete replacements for Portland cement to enhance soil characteristics (Singh et al., 2020; Noaman et al., 2022; Alhassani, 2021). The promotion of using these materials contributes to environmental sustainability by recycling waste.

Furthermore, the proposed empirical equations are valid only for the medium-dense clayey sands at a water content close to the optimum water content and cement contents (0 to 3%). Further studies are required to expand the results to other relative densities and other ranges of water content. It is also worth noting that the initial water content used in preparing the samples was the optimum water content obtained by compaction tests at each cement content. This water content decreases over time due to the hydration process of cement (Lorenzo et al., 2006).

## CONCLUSIONS

1. For all cemented samples, the stress-strain curves demonstrate a steady rise in the stress with the strain up to a peak value at which a sudden brittle failure is followed by a downward trend (strain softening).
2. There was a continuous increase in the UCS, $E_{50}$ and $E_A$ with the increase in cement content, clay content or curing period.
3. Increasing the curing time causes a reduction in the failure strain.
4. For the same cement content and the same curing time, increasing the clay content makes the samples more ductile and break at a higher strain.
5. For engineering projects, it is advised to achieve the optimum water content in the field to obtain the highest possible deformability from the cemented soil.
6. Two empirical equations have been developed on the basis of the cement and clay contents to predict the UCS of cemented clayey sand at any curing time (≤ 28 days).

### Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

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### Conflict of Interests

The authors have no relevant financial or non-financial conflict o f interests to disclose.

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