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Effect of cement stabilization on geotechnical properties of sandy soils

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Abstract. An experimental program was performed to study the effects of cement stabilization on the geotechnical characteristics of sandy soils. Stabilizing agent included lime Portland cement, and was added in percentages of 2.5, 5 and 7.5% by dry weight of the soils. An analysis of the mechanical behavior of the soil is performed from the interpretation of results from unconfined compression tests and direct shear tests. Cylindrical and cube samples were prepared at optimum moisture content and maximum dry unit weight for unconfined compression and direct shear tests, respectively. Samples were cured for 7, 14 and 28 days after which they were tested. Based on the experimental investigations, the utilization of cemented specimens increased strength parameters, reduced displacement at failure, and changed soil behavior to a noticeable brittle behavior.

Keywords: lime portland cement; stabilization; unconfined compressive strength; shear strength parameters; brittle behavior

1. Introduction

The lack of accessibility of high quality materials and the increased costs associated with the use of these materials will finally necessitate engineers to use local soils. In such cases, ground improvement behaved satisfactorily in many conditions.

Ground improvement can be defined as the procedure of increasing shear strength parameters and decreasing the permeability and compressibility of the soil. Different methods can be used to improve the geotechnical properties of the problematic soils that one of them is using additives. Additive stabilization is achieved by the addition of proper percentages of cement, lime, fly ash, bitumen, or combinations of these materials to the soil. The selection of type and determination of the percentage of additive to be used is dependent upon the soil classification and the degree of improvement in soil quality desired (Engineering Manual 1110-3-1371984).

Sandy soils cover widespread areas in the north of Iran. Liquefaction, low bearing capacity, high potential of failure, high groundwater table and variation of soil density and strength in different places create major problems for the construction of infrastructure in these areas (Aiban 1994). There are several methods for overcoming these problems that soil stabilization is one of

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them. The stabilization of soils with cement is an attractive technique, because of economical and environmental issues, avoiding the use of borrow materials from elsewhere.

The use of cement as a stabilizing agent in various applications in ground engineering is quite common. The addition of small amounts of cement, that is, up to 2%, modify the properties of the soil, while large quantities cause substantial changes in these properties (Bell 2005). Any kind of soil can be stabilized with cement except the soils with organic materials and clay with high plasticity. According to ACI committee in (1997), soils containing more than 2% of organic materials are not suitable for stabilizing with cement, because the organic materials may prolong or hinder the cement hydration and finally reduce the strength. Cemented sands situate in a wide range of materials that show a behavior between the soil and rock, often with characteristics of both (Sitar 1983).

The main parameters in compaction properties of artificially cemented soils depend on many factors, such as soil type and properties, stabilizing agent and stabilizer content as well as the method of compaction. The addition of cement changed optimum moisture content and maximum dry unit weight of the soils, but the rate of changes is not predictable (ACI 1997). The optimum moisture content and maximum dry unit weight, increase and decrease, respectively, with increasing amounts of CKD (Miller and Azad 2000). The addition of cement increased optimum moisture content and decreased maximum dry unit weight of the soils (Sarriosseiri and Muhunthan 2009).

The effect of cement content and curing time on the stress-strain behavior and unconfined compressive strength of artificially cemented sands for different curing times have been investigated in the past by several authors. The parameters which defined as key parameters in strength of artificially cemented sand are water content, cement content, porosity and porosity/volumetric cement content ratio (Consoli *et al*. 2007). Substantial reduction in plasticity index and significant increase in strength, modulus of elasticity can be achieved by cement stabilization (Uddin *et al*. 1996). Addition of CKD to soil can substantially improve the unconfined compressive strength. The improvement is more significant for soils with low PI (Miller and Azad 2000). Das *et al*. (1995) carried out several unconfined compression tests on the artificially cemented sands. They concluded that unconfined compression strength increases with increase in cement content while compressive strains at failure decrease. Haralambos (2009) investigated that the soil type influences significantly the increase of unconfined compressive strength due to cement addition. The addition of cement to all soil types increased the compressive strength and stiffness of the soil-cement mixture. Consoli *et al*. (2009) reported that the addition of cement to the sand, in contents up to 10% by weight of dry sand, significantly increased stiffness and peak strength, and changed the sand behavior to a noticeably more brittle behavior. Consoli *et al*. (2010) considered that the voids/cement ratio (η/C_v) has been shown to be an appropriate index parameter to evaluate both splitting tensile and unconfined compressive strength of sand-cement mixtures.

The findings of different researchers on the role of the stabilizing agent on shear strength parameters have not been completely consistent. It has been extensively reported that a stabilizing agent will increase the effective cohesion (Mitchell 1976). While some of the researchers like Reddy and Saxena believe that stabilization with cement has insignificant effect on the internal friction angle, other ones such as Lambe, Balasubramaniam *et al*. believe that stabilization by cement lead to a significant increase in internal friction angle (Lo and Wardani 2002). Balmer (1958) reported that the mean values of internal friction angle varied from 36.1° to 43.8° for fine and coarse grained stabilized soils, respectively. According to Wissa's observations in (Wissa *et al*.

1965), though cohesion increases with curing time, internal friction angle remains almost constant. Al-Aghbari *et al*. (2009) investigated the effect of stabilization of sandy soils by cement on shear strength parameters and concluded that the shear strength parameters increase with increasing stabilizer content and curing time. Schnaid *et al*. (2001) reported that the shear strength of the cemented soil measured in conventional triaxial tests can be determined as a function of the unconfined compressive strength and the uncemented friction angle.

The artificially cemented soils noticeably increase the elastic modulus and the peak strength, but they represent brittle stress–strain behavior especially at higher cement contents (Schniad *et al*. 2001). This brittle behavior can cause the sudden failure of soil structures that are stabilized with these materials; therefore, the usage of artificially cemented soils may not be allowed particularly at a shallow depth, because of low confining pressures (Park 2011). One of the most key methods to overcome this problem is the application of natural and artificial fibers (Kaniraj and Havanagi 2001, Consoli *et al*. 2003).

This study therefore aims to quantify the influence of the amount of cement and the curing time on the strength parameters of artificially cemented sandy soils through unconfined compressive and direct shear tests.

2. Materials

The soil used in the present study was obtained from shores of Caspian sea (in the city of Mahmoud-Abad located in the north of Iran). The grain size distribution of this sand is shown in Fig. 1 (ASTM D-421 2002, ASTM D-422 2003). The properties of the sand, which is classified as a fine-grained, poorly graded sand (SP) according to the Unified Soil Classification System (ASTM D-2487 2006), are shown in Table 1.

Lime Portland cement was used in this research. The most important reasons of choosing this kind of cement as the stabilization agent were: Increasing the initial resistance, decreasing the sensitively, and better workability than ordinary Portland cement. Some of the most important physical characteristics of this kind of cement are tabulated in Table 2 (ISIRI 4220 2006).

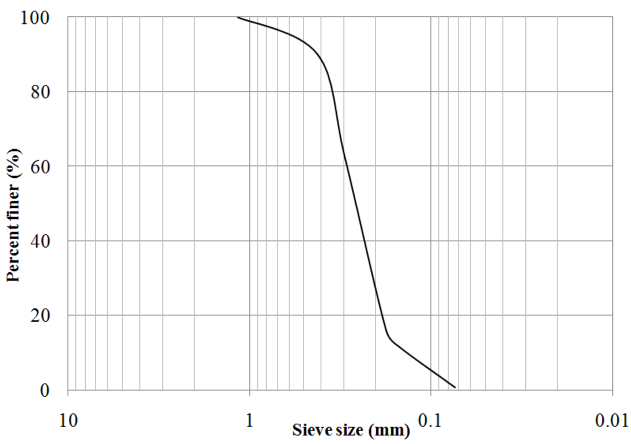


Fig. 1 Grain size distribution curve for Mahmoud-Abad sand

Table 1 Properties of Mahmoud-Abad sand

Effective grain size (D_{10})	(D_{30})	Medium grain size (D_{50})	(D_{60})	Coefficient of uniformity (C_u)	Coefficient of curvature (C_c)	Specific gravity of solids (G_s)	Angle of internal friction (in the densest condition)
0.15 mm	0.21 mm	0.27 mm	0.29 mm	1.93	1.	2.74	36°

Table 2 Physical properties of lime Portland cement

Specific surface (Cm^2/g)	Autoclave expansion (%)	Initial setting (Min)	Compressive strength (Kg/Cm^2)		
			3 days	7 days	21 days
> 3000	< 0.8	> 75	> 120	> 200	> 330

(a) (b)

Fig. 2 Curing of specimens for: (a) UCS; and (b) direct shear tests

3. Specimens preparation

3.1 Effect of geotextile reinforcement

For the unconfined compression and direct shear tests, cylindrical (38 mm × 84 mm) and cube (60 mm × 60 mm × 20 mm) specimens were used, respectively. After the soil and cement were mixed thoroughly until a uniform color was observed, then the water was added continuing to the soil cement mixture. The amount of cement for each mixture was calculated based on the weight of dry soil. All specimens were prepared at their maximum dry unit weight and optimum moisture content, corresponding to the values obtained in standard Proctor compaction tests accomplished on both cemented and uncemented soils (ASTM D-698 2000). The specimens were statically compacted in three identical layers, so that each layer reached the determined dry unit weight. It should be noticed that for the direct shear test specimens, the level of the shear surface passed through the mid-height of the middle layer. The time used to prepare, mix and compact the specimens was always less than 1 h, which is shorter than the initial setting time of this kind of cement (75 min). Two sets of specimens were prepared for each test. The specimens were wrapped in plastic bags for 7, 14 and 28 days curing time before testing (Figs. 2(a) and (b)).

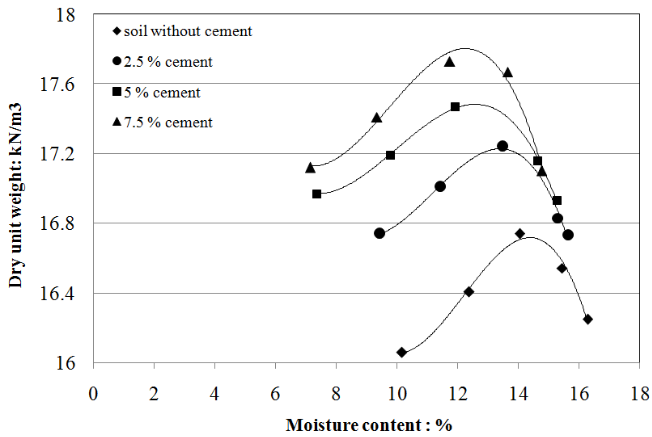


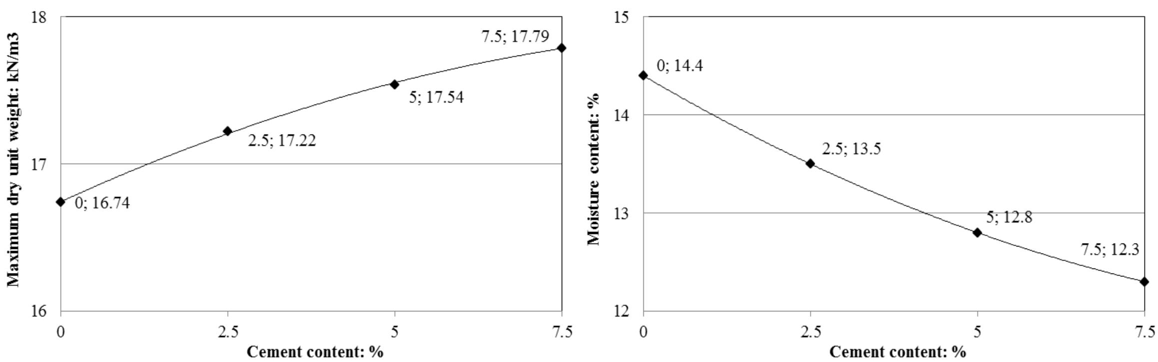
Fig. 3 Effect of cement stabilization on compaction curves

It's necessary to note that the technique of undercompaction proposed by Ladd (1978) was not utilized here for making the samples, because the samples were made at maximum dry unit weight. Baldi *et al*. (1988) showed that the use of such technique is necessary only for specimens as loose as 20% relative density.

4. Laboratory testing program and result

4.1 Compaction tests

Cement was added in amounts of 2.5%, 5% and 7.5% by dry weight of the soil. The soil and cement were mixed thoroughly to a uniform color, and then the water was added to facilitate the mixing and compaction process.



(a) (b)

Fig. 4 Effect of cement content on: (a) maximum dry unit weight; and (b) moisture content

Standard compaction tests were performed on both cemented and uncemented soils to investigate the optimum moisture content and the maximum dry unit weight in accordance with ASTM D-698, including A method (the choice was based on the material gradation). The results of the compaction tests are shown in Fig. 3.

It is obvious that, with increasing cement percentage, the maximum dry unit weight increases and optimum moisture content decreases. Cement addition influences soil-cement mixture compatibility. Changes in compaction parameters (γ_{dry} and w_{opt}) are affected by higher specific gravity value of cement than sand, alterations in the grain-size distribution of the mixture and reduction in moisture content (Al-Aghbari *et al*. 2009, Zabielska 2008). The amount of alterations in γ_{dry} is more enunciated at the lower percentage of stabilizer content.

As shown in Fig. 4, changes in compaction characteristics are significant at lower percentages of cement content. However at higher percentages of cement content, the changes in compaction characteristics of stabilized soil are minimal.

4.2 Drying rate of the soil

Drying rate of the soil (Solidification) is the process that removes excess moisture from soil mass by hydration reaction induced by addition of stabilization agent (Bennert *et al*. 2000). After the soil and water were mixed thoroughly until a certain level of moisture content, different amounts of cement was added to the mixture, then changes in moisture content were measured with time.

The effect of cement stabilization on the solidification properties of Mahmoud-Abad soil is shown in Fig. 5.

These observations were performed at room temperature 21.5 ± 2°C for different cement contents. It can be seen that addition of cement leads to considerable reduction in moisture content.

The above results show that the addition of cement can facilitate the compaction of the sandy soils that are encountered wet side of optimum water content. This figure can be used to identify the amount of the moisture content reduction in preparation of samples (time used to prepare, mix and compact the specimens), and this is one of the most applications of the above figure.

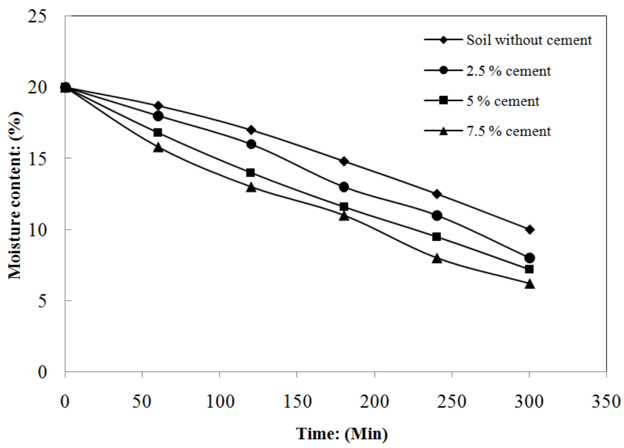


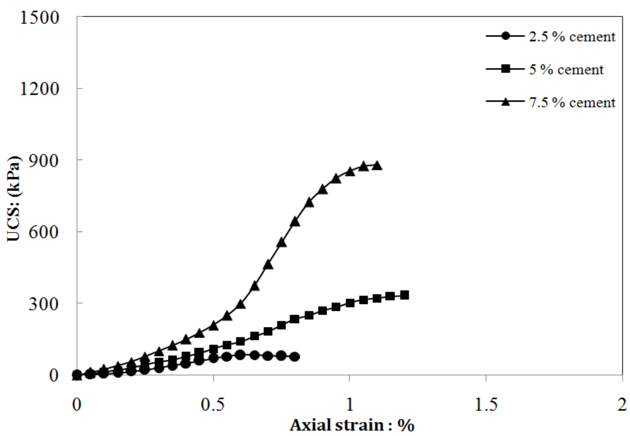
Fig. 5 Solidification characteristics of sandy soil with different cement contents

4.3 Unconfined compression tests

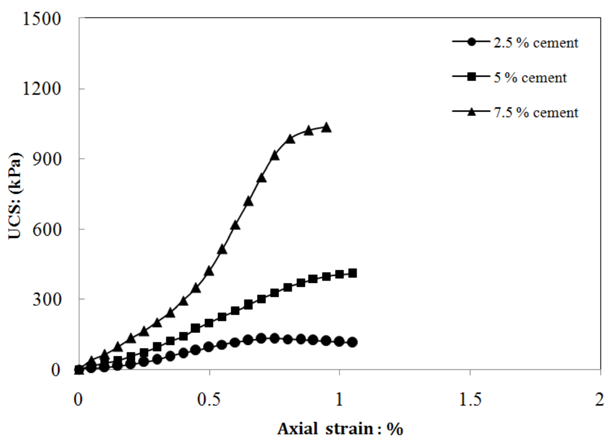
The unconfined compression (UCS) test is one of the most important laboratory tests in order to evaluate the effectiveness of the stabilization with cement or other additives. The UCS test determines the strength of stabilized soils at faster speed while being simple, reliable and cheap (Consoli *et al*. 2011). These tests were performed in accordance with ASTM D-2166 (2000). According to the mentioned standard, loading speed should be about 0.5 to 2% axial strain/min. Stiff or brittle materials that will exhibit small deformations at failure should be tested at a lower rate of strain, therefore the rate of displacement adopted was 0.53 mm/min.

Figs. 6(a)-(c)) illustrate the stress-strain relationship of stabilized specimens with different amounts of cement, namely, 2.5, 5, and 7.5%, respectively, considering the curing time.

It is evident that the maximum axial stress increases considerably due to cement stabilization,

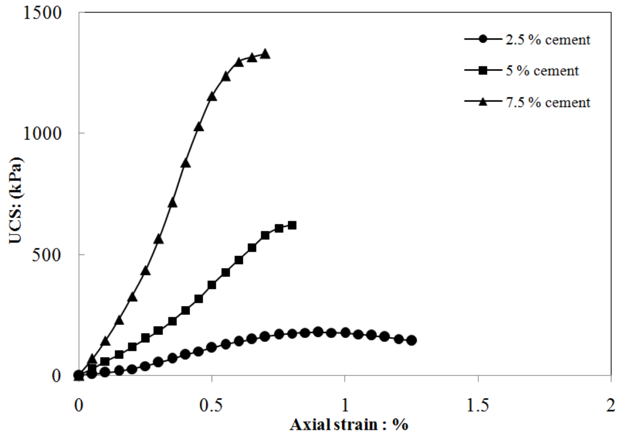


(a)



(b)

Fig. 6 Effect of cement stabilization on unconfined stress-strain behavior of soil: (a) 7; (b) 14; and (c) 28 days of curing time



(c)

Fig. 6 Continued

but the corresponding strain to maximum axial stress decreased. In other words, the utilization of stabilized soil increased UCS, reduced displacement at failure, and changed soil behavior to a noticeable brittle behavior.

Fig. 7 illustrates the fitted lines for the maximum UCS of the stabilized specimens as a function of the cement percentage (C), considering the curing time (these relationships are only for the soil studied here). It can be seen that the cement content has a great effect on the peak strength of stabilized soil. The addition of small amounts of cement, that is, up to 2%, modify the properties of a soil (strength parameters in this article), while large quantities cause radical changes in these properties (Bell 2005). It can be observed that UCS increases approximately linearly with the increase in the cement content. The values of UCS of stabilized sandy soils in this article agree well with published data for this type of soil in different literatures.

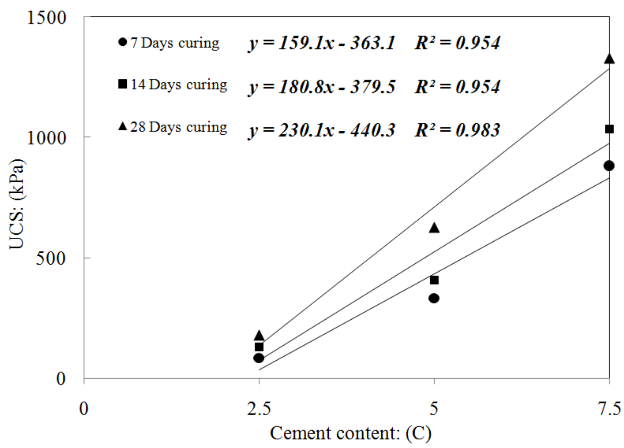


Fig. 7 Effect of cement contents on maximum unconfined compressive strength

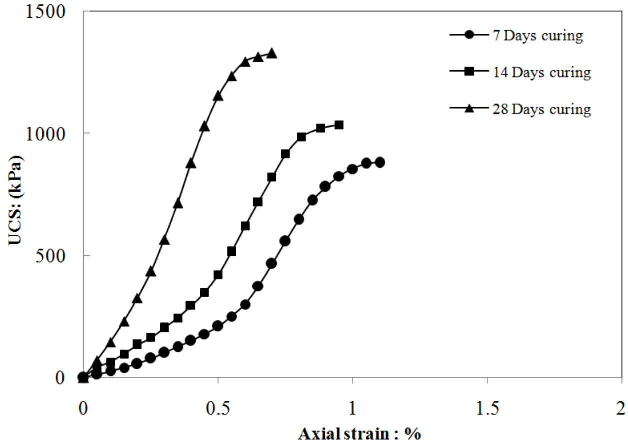


Fig. 8 Effect of curing time on stress-strain behavior for 7.5% cement content

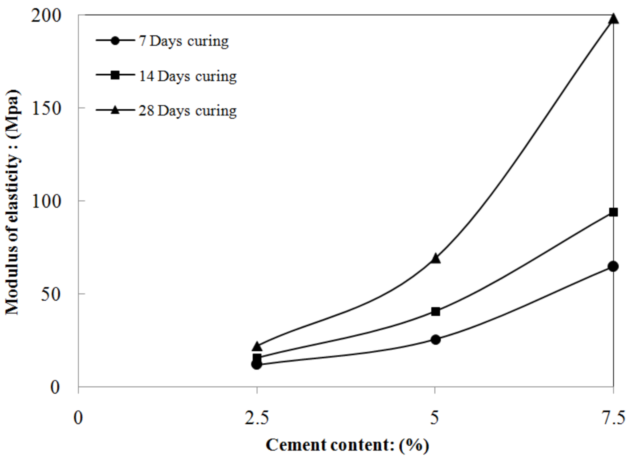


Fig. 9 Effect of cement content and curing time on modulus of elasticity

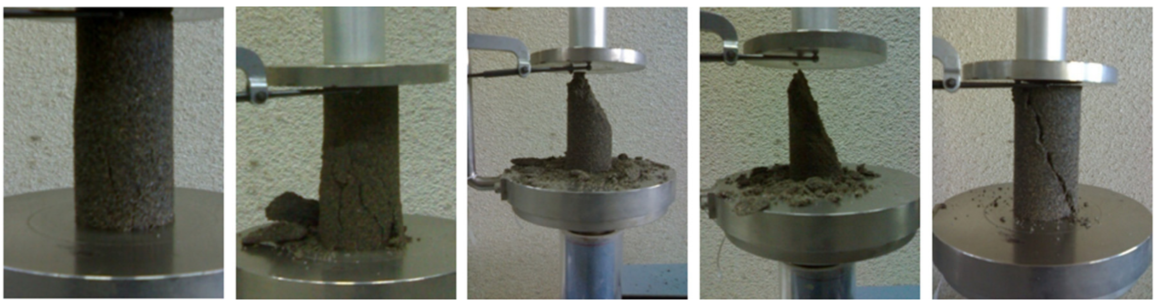


Fig. 10 Failure types of stabilized specimens

Fig. 8 demonstrates the stress-strain curves of stabilized specimens for cement content equal to 7.5% and curing times equal to 7, 14, and 28 days (as an example). The figure shows that with increasing the curing time, the maximum UCS increase. The effect of curing time on maximum UCS is more pronounced for higher amounts of cement. It should be reminded that the stress-strain curves for the different amounts of cement are similar, apart from the difference in peak stress.

Fig. 9 shows the effect of cement stabilization on modulus of elasticity at 50% of maximum axial stress (E_{50}). Significant improvement in modulus of elasticity is attained by cement stabilization and curing time especially for cement contents greater than 5%. It can be concluded that stabilized soils with cement will tolerate much smaller deformation.

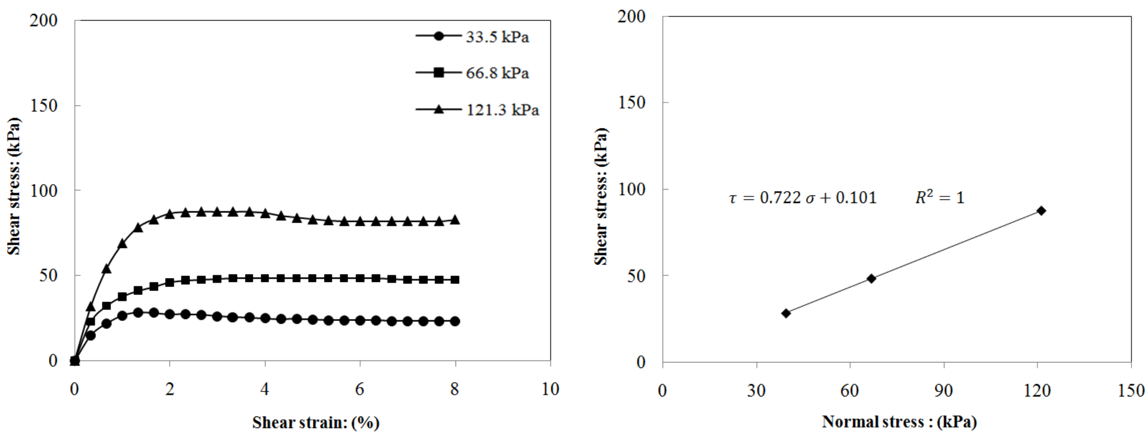
Fig. 10 shows failure types of stabilized specimens at the end of the UCS tests.

4.4 Direct shear tests

The tests were performed using a conventional direct shear apparatus according to BS 1377: PART 7 (1990) to investigate the effect of cementation on stress-strain and shear strength characteristics of cemented and uncemented sandy soils. The normal stress was chosen 33.5, 66.8 and 121.3 kPa for all the specimens. The shear loading was applied at a rate of 0.12 mm/min. The failure envelope of soil is defined based on Mohr-Coulomb failure criterion.

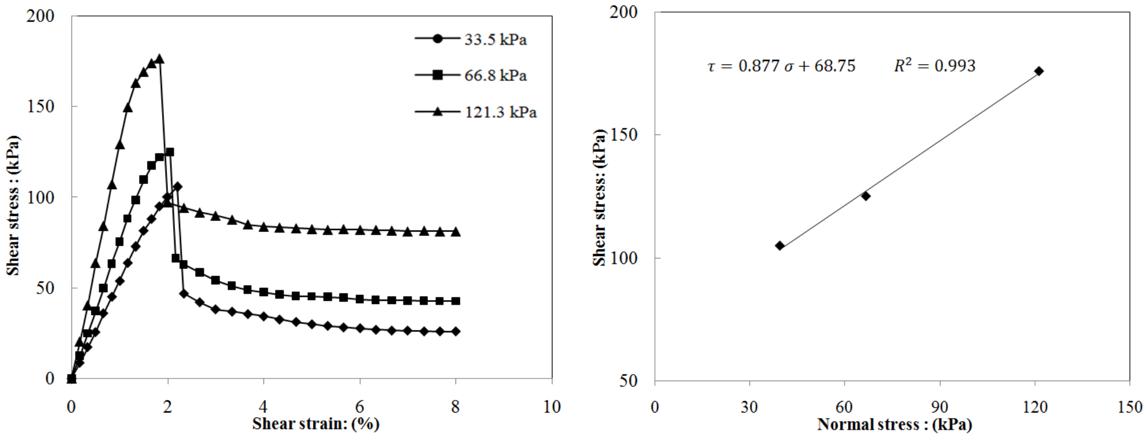
The effect of stabilization on shear stress-strain behavior of cemented and uncemented sandy soils associated with Mohr-Coulomb failure envelopes are presented in Figs. 11(a)-(d)) (in order to summarize, it is avoided to present the stress-strain curves for other curing times).

It can be observed that cement stabilization leads to significant increase in maximum shear stress, of course for a certain amount of normal stress. Another important point which can be concluded in this section is that the maximum shear stress dramatically dropped after the failure which is indicative of noticeable brittle behavior.

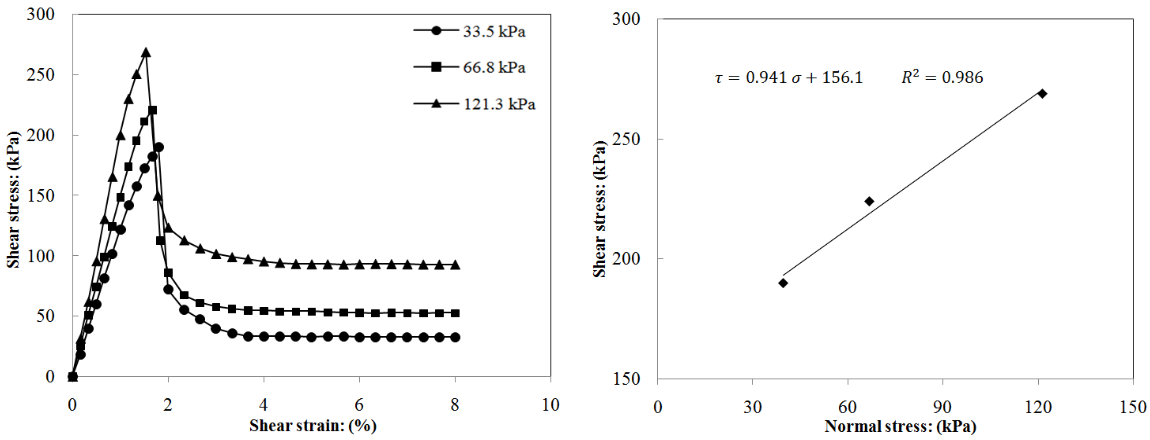


(a)

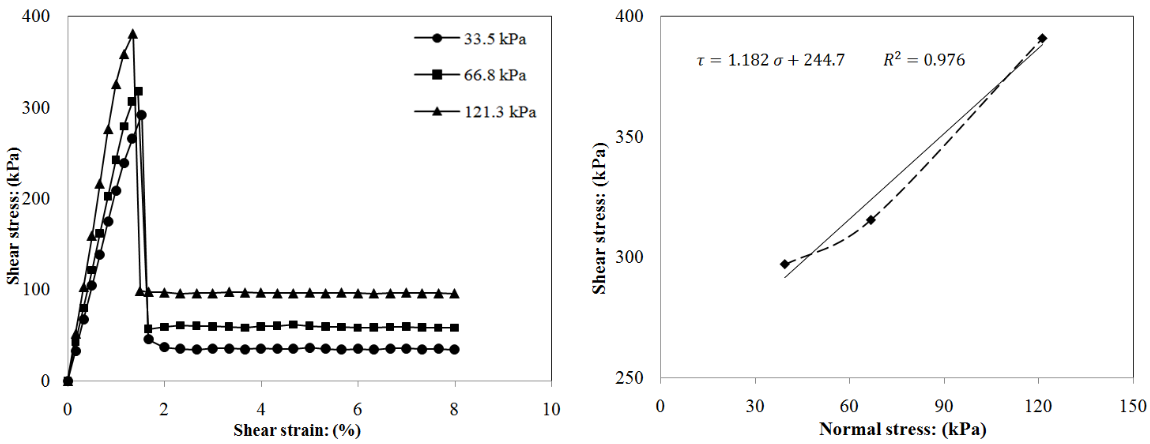
Fig. 11 Effect of cement stabilization on shear stress-strain behavior of soil for 28 curing time in direct shear test associated with Mohr-Coulomb failure envelope: (a) soil without cement; (b) 2.5%; (c) 5%; and (d) 7.5% cement content



(b)



(c)



(d)

Fig. 11 Continued

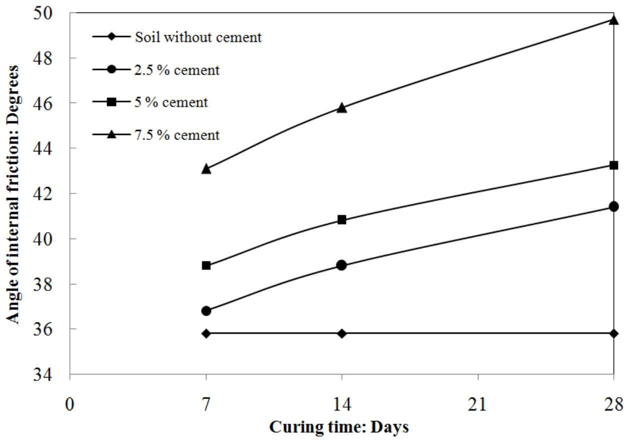


Fig. 12 Shear strength parameters of cement-stabilized soil for different cement content and curing time: (a) cohesion; (b) angle of internal friction

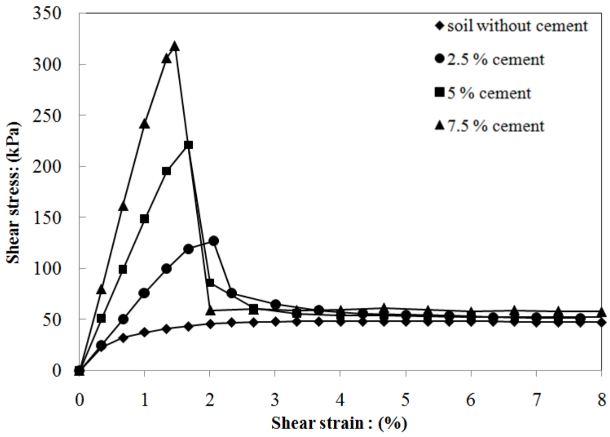


Fig. 13 Stress-strain relationship of cemented and uncemented sandy soils for normal stress of 66.8 kPa

Fig. 14 failure type of stabilized specimen at the end of the direct shear test ig. 11 also illustrates the Mohr-Coulomb failure envelopes for cemented and uncemented specimens. It is evident that the Mohr-Coulomb failure envelope for cement stabilized soils is curved with increasing cement content (see R^2). These conclusions confirm the findings of researchers (Abboud 1973).

Figs. 12(a)-(b) Show the effect of cement stabilization on shear strength parameters based on Mohr-Coulomb failure criterion, namely, cohesion and internal friction angle. The data indicate that the shear strength parameters increase with increasing cement content and curing time, but the effect of curing time is more moderate than cement content.

Fig. 13 shows the variation of shear stress-strain curves with normal stress (for example 66,8 kPa) for specimens at different values of cement content. It can be concluded that after peak shear stress, the maximum shear stress dropped towards approximately the same value found for the direct shear test carried out on the natural soil (uncemented sandy soil).

Fig. 14 shows a failure type of stabilized specimen at the end of the direct shear test.

5. Conclusions

This paper presented the effect of curing time on strength parameters of sandy soils stabilized with different amounts of lime portland cement. From the data presented in this paper, the following conclusions can be drawn:

- The optimum moisture content and maximum dry unit weight, decrease and increase, respectively, with increasing amounts of lime portland cement.
- The addition of few percentages of lime portland cement increased drying rate of the soils considerably. These effects are high during the initial stages.
- The addition of lime portland cement even in small amounts can significantly improve the soil strength. The unconfined compression strength increased approximately linearly with an increase in the cement content.
- Increasing the curing time increased the UCS, but the effect of curing time on maximum UCS is more pronounced for higher amounts of cement.
- The stabilized soil exhibits brittle behavior during UCS test. Significant increases in modulus of elasticity and decreases in the strain at failure occur with the addition of lime portland cement.
- The shear strength parameters, namely, cohesion and internal friction angle increase with increasing lime portland cement content. The substantial increase in cohesion is evident than internal friction angle.
- There is a considerable increase in cohesion and internal friction angle in samples containing lime portland cement with increasing curing time, but the effect of curing time is more moderate than cement content.
- After peak shear stress, the maximum shear stress dropped towards approximately the same value found for the direct shear test carried out on the natural soil.

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