Undrained Shear Strength and Swelling Characteristics of Cement Treated Soil

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ABSTRACT

This study investigates the influence of cement addition on the behavior of an expansive soil from Jordan. A wide range of cement content varying from 0 to 25% by dry weight of soil was used. This study shows that the liquid limit of the treated soil decreases drastically for cement content of up to 6%, then sharply increases for cement content in the range of 6 to 10% after which the liquid limit becomes practically constant. This study shows also that the swell potential of the treated soil decreases drastically for cement content of up to 4%, then sharply increases for cement content in the range of 4 to 6% after which the swell potential may decrease or may become constant depending on the initial water content. The undrained shear strength was generally observed to increase with the increase of cement content from 0 to 20%; however, the maximum rate of this increase was observed to be in the range of cement content from 6 to 10%. These results are interpreted in terms of cation exchange, flocculation and pozzolanic reactions that are associated with cement addition to soil.

KEYWORDS: Undrained shear strength, Swell potential, Expansive soil, Liquid limit, Plasticity index, Cement content.

INTRODUCTION

Expansive soils are those soils that swell when the moisture content is increased and shrink when the moisture content is decreased. Consequently, expansive soils cause distress and damage to structures founded on them.

Extensive studies have been carried out on the stabilization of expansive soils using various additives such as cement, lime, fly ash, industrial waste products, calcium chloride, potassium chloride and phosphoric acid (Croft, 1967; Basma and Tuncer, 1991; Nelson and Miller, 1992; Al-Zoubi, 1993; Bell, 1996; Locat et al., 1996; Abdullah et al., 1997; Abdullah et al., 1999; Rao et al., 2001; Feng, 2002; Al-Rawas et al., 2002) in addition to the mechanical improvement of soils such as the use of vertical drain with surcharge (Mesri et al., 1994; Terzaghi et al., 1996).

Because of the arid nature of the climate in Jordan, which is associated with high evaporation rates, there is always a moisture deficiency in soils. Hence, ground heave is very likely to take place in all soils (possessing swelling potential) when subjected to water. As a result, some of these structures in many areas of Jordan where expansive soils exist suffered from serious distress and damage and in some cases houses were demolished. Despite of that, the literature indicates minimal studies on the stabilization of expansive soils in Jordan. Therefore, this study was carried out to add to the literature on the behavior and treatment of expansive soils of Jordan.

The experimental studies reported in the literature (e.g., Nelson and Miller, 1992; Lawton, 1996; Terzaghi et al., 1996; Feng, 2002; Al-Rawas et al., 2005) generally

Accepted for Publication on 18/12/2007.

show that the addition of cement to clay soils reduces the liquid limit, plasticity index and swelling potential and increases the shear strength. However, the usual range of cement content in most of these studies varies from 3 to 15 %. Furthermore, rare were these studies carried out to assess the influence of cement addition on all the consistency limits, swell potential and shear strength of the same soil together at the same time.

In this study, the influence of addition of cement on the Atterberg limits, percent free swell and undrained shear strength of a highly expansive clay soil obtained from Jordan is investigated utilizing a wide range of cement content that varies from 0 to 25 % by dry weight of soil. Experimental results of tests conducted on specimens with and without cement treatment are compared and evaluated.

EXPERIMENTAL PROGRAM

Selected soil and its classification

The soil utilized in this study was obtained from Al-Marj area- Al-Karak Governate-Jordan. The natural (untreated) soil has a high liquid limit of 53% and a high plasticity index of 26%. According to the Unified Soil Classification System (Fig. 1), the soil can be classified as inorganic clay of high plasticity (CH). This soil can also be classified as having high swelling potential when compared to the criteria of identifying swell potential, such as that of Daskshanamanthy and Raman (1973).

Cement treatment

In this study, normal Portland cement manufactured by the Jordan Cement Company is utilized for the treatment of the selected soil in order to modify its properties such as swell characteristics and undrained shear strength.

Portland cement contains tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A) and tetracalcium alumino-ferrite (C_4A) (Lea, 1956). These four main constituents are major strength producing compounds. When the pore water of the soil is encountered with the cement, the major cementing products are hydrated calcium silicate (CSH), hydrated calcium aluminates (CAH) and hydrated lime $Ca(OH)_2$. The cement treated clay also induces pozzolanic reaction because the $Ca(OH)_2$ is produced from the hydration process. In other words, when cement is added to clayey soils in the presence of water, a number of reactions occur leading to the modification of soil properties. These reactions include cation exchange, flocculation, carbonation and pozzolanic reaction (Al-Rawas et al., 2005). The cation exchange takes place between the cations associated with the surfaces of the electrically charged clay particles and calcium cation of the cement. The effect of cation exchange and attraction causes clay particles to become close to each other, forming flocs; this process is called flocculation. Flocculation is primarily responsible for the modification of the engineering properties of clayey soils. On the other hand, cement stabilization develops from the cementitious links between the calcium silicate and aluminate hydration products and the soil particles (Croft, 1967; Al-Rawas et al., 2005).

Initial testing states of water content and dry density

Because the swelling potential of an expansive soil depends on the initial condition of the soil, it was essential to test specimens at identical placement conditions. Therefore, a unified procedure and special molds were utilized in order to achieve reproducibility of identical specimens for both the free swell and the unconsolidated undrained (UU) triaxial compression tests.

In this study, two different states of water content at the same dry density were selected in order to investigate the effect of water content on the swelling characteristics of the utilized soil in its natural (untreated) and treated conditions. The two states of water content and dry density (states 1 and 2) are shown in Fig. 2, which depicts the dry density versus water content relationship for the natural (untreated) soil utilized in this study. Furthermore, because the swelling potential of a soil also depends on the surcharge pressure applied to the sample, an initial surcharge pressure (seating pressure) of 7 kPa was used for the entire testing program. The undrained strength tests were conducted on specimens compacted at one state of water content and dry density (i.e., State 1 of Fig. 2).

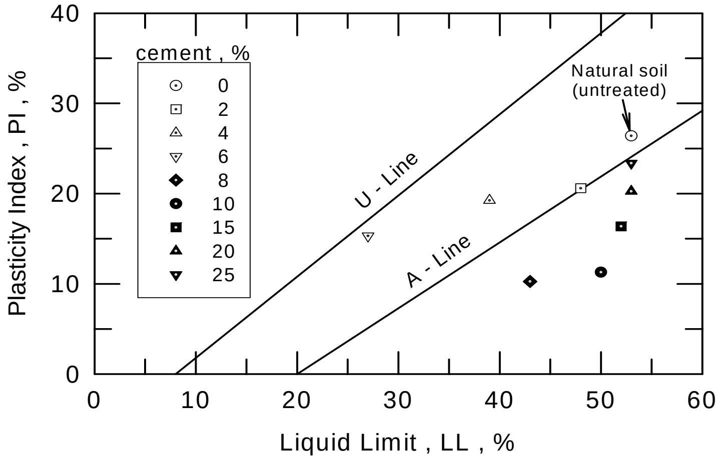

Figure (1): Effect of cement addition on the classification of the soil utilized in this study.

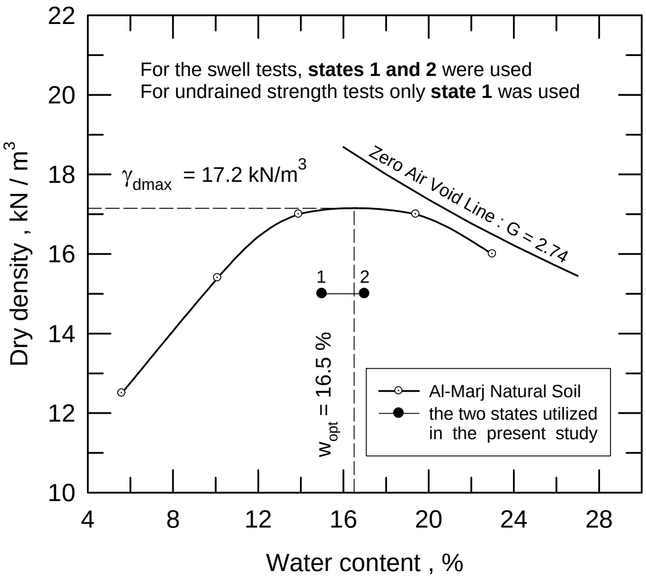

Figure (2): Dry density vs. water content relationship (standard Proctor compaction tests) for Al-Marj Soil showing the states of water content and dry density considered in this study for swell and strength tests.

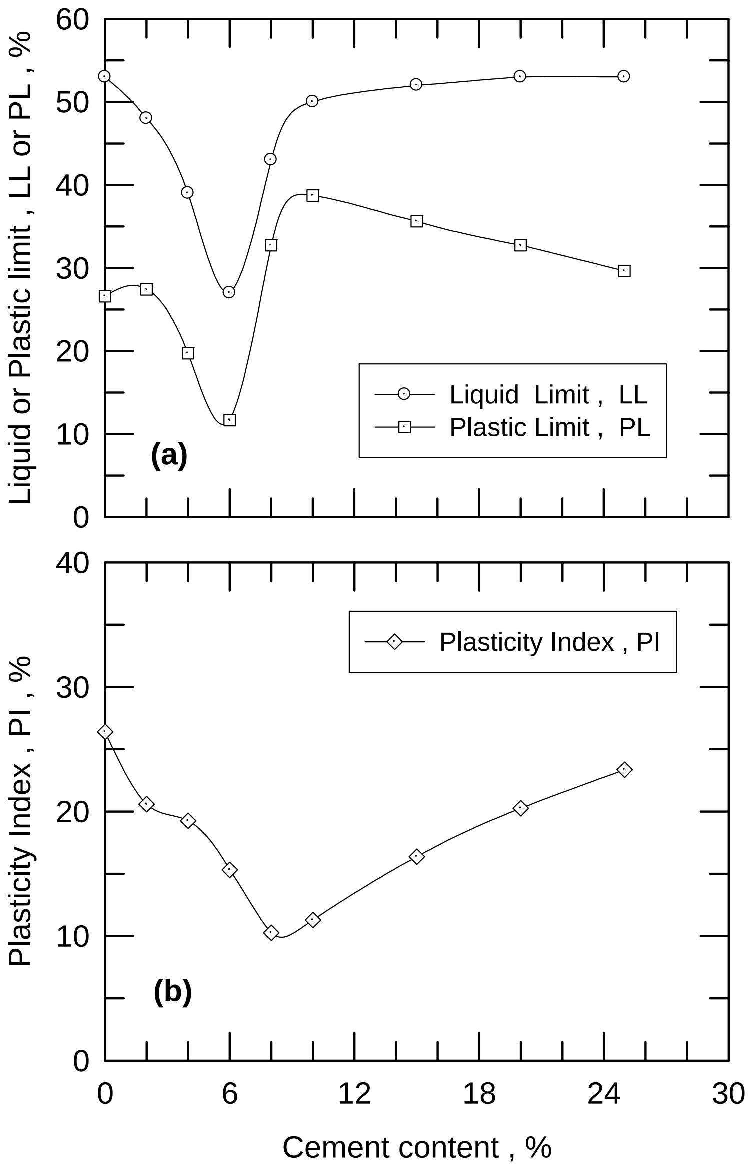

Figure (3): Effect of cement content on the liquid limit, plastic limit and plasticity index of Al-Marj soil.

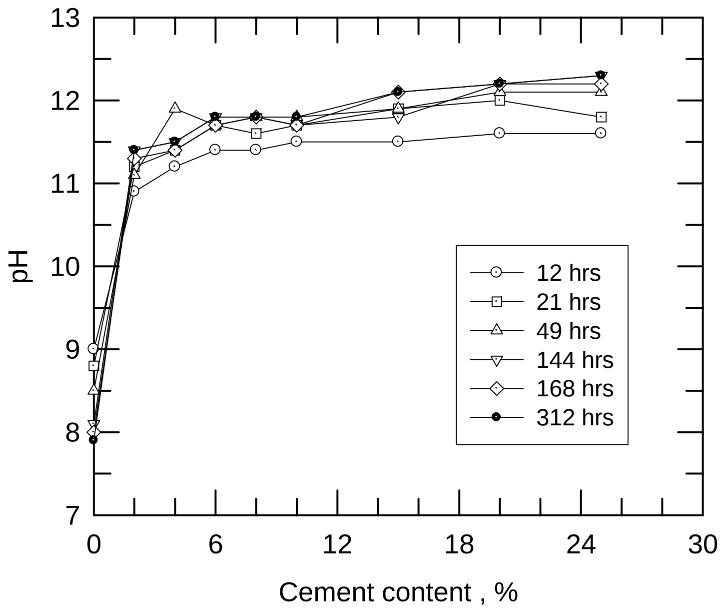

Figure (4): Effect of cement content and storing time on the pH value of the treated soil.

Soil preparation for swelling potential and strength tests

After it was brought to the laboratory, the soil was repeatedly broken into small pieces, air dried and pulverized using a plastic hammer. The air dried soil was further pulverized to minus 20 sieve size. At this stage, the soil was ready for remolding specimens for both the free swell and strength tests.

For both types of tests, an amount of air dried soil required for the desired dry unit weight was weighed and mixed with the specified cement content (i.e., 2%, 4%, 6%, 8 %, 10, 15%, 20% or 25% by dry weight of the soil). The water needed for any particular water content was also weighed. The soil-cement mixture was thoroughly mixed with distilled water until a homogeneous mixture was achieved. The wet soil-cement mixture was then placed into the special mold and compacted to exactly fit the oedometer ring to produce a specimen of 20 mm high and 71 mm in diameter in the case of free swell test and to produce a specimen of 76 mm high and 38 mm in diameter for the UU tests. All the specimens were tested immediately after preparation except where reported otherwise.

The liquid limit was obtained by the Casagrande apparatus. A soil batch of about 200 gm of the soil was first mixed with the specified cement content and then distilled water was added to the soil-cement mixture until it became a paste. Then the soil paste was carefully covered and stored for 24 hrs to allow the water to be distributed uniformly within the sample. In order to avoid waiting and to minimize the effect of testing time on the results of liquid limit, several batches were prepared at different water content and were used for the determination of the liquid limit instead of using only one batch for this purpose.

Percent free swell is defined herein as the increase in vertical height of a specimen, expressed as a percentage of the initial height, due to the increase in moisture content under a surcharge of 7 kPa. The standard oedometer apparatus was used to conduct the swell test. The specimen was first loaded to the seating pressure then it was flooded with distilled water and allowed to swell under the seating pressure. Dial gauge readings were taken at 0, 0.5, 1.0, 2.0, 4.0, 8.0, 15.0, 30.0, 60.0, 120 and 1440 min.

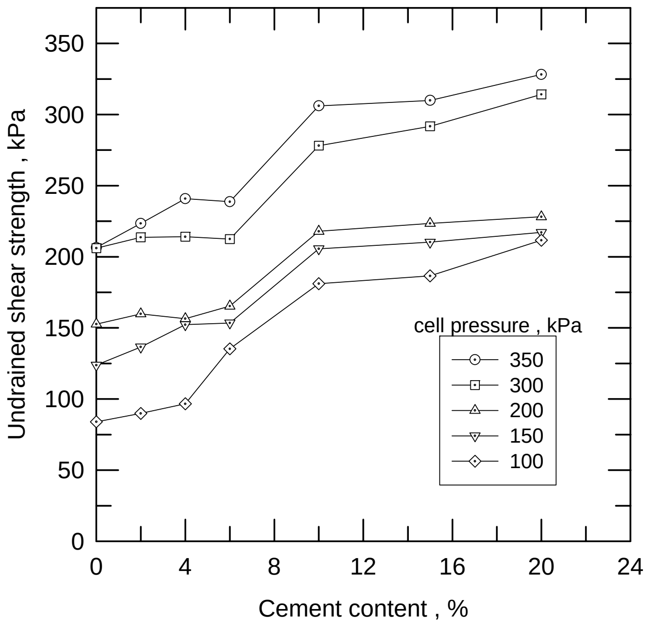

Figure (5): Effect of cement content on UU strength for different values of cell pressure.

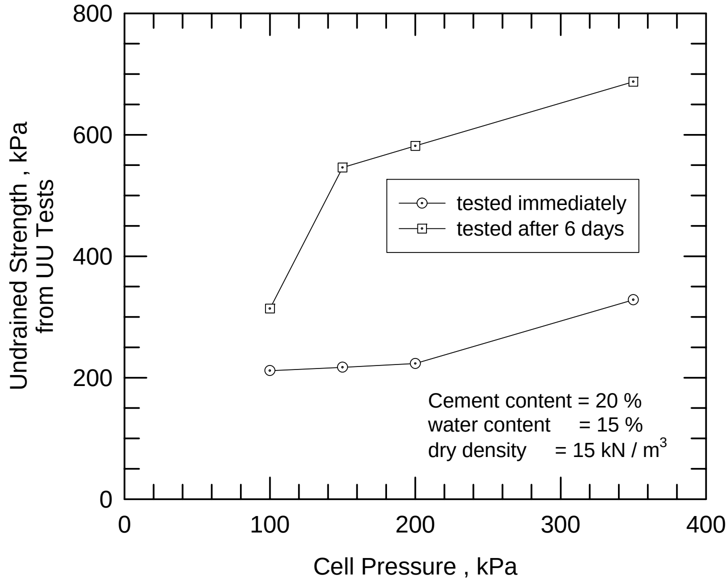

Figure (6): Effect of cement content and storing period on the undrained strength.

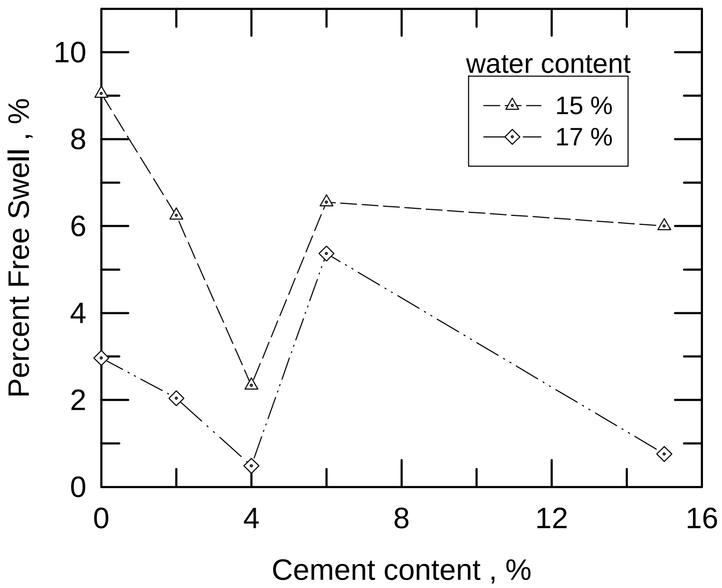

Figure (7): Relationship between percent free and liquid limit of treated soil at different initial water content at a pre-specified dry density.

Shear strength is defined herein at the peak value of the stress-strain curve obtained from UU tests that were conducted at cell pressures of 100, 150, 200, 300 and 350 kPa. Wherever the peak value was not observed, the shear strength was defined at 15% strain. The specimen was first sealed and loaded to the desired cell pressure, then the axial load was increased at a rate of 0.5 mm/min until the failure of the specimen. Axial deformation and axial load were recorded during this shearing stage of the test.

RESULTS AND DISCUSSION

Effect of cement content on the Atterberg limits

The liquid limit, plastic limit and plasticity index of the untreated and treated samples are shown in Fig. 3 as a function of the cement content that ranges from 0 to 25% by dry weight of soil. Figure 3 (a) shows that the liquid limit decreases drastically in the range of cement content from 0 to 6%, whereas it (the liquid limit) drastically increases in the range of cement content from 6 to 10 % after which the liquid limit increases very slowly and becomes practically constant at large cement content. The liquid limit exhibits a minimum value at an optimum cement content of about 6 %. The plastic limit follows the similar trend as that of the liquid limit for cement content of up to 10%; however, the plastic limit decreases steadily after 10% of cement content. Figure 3(b) shows that the plasticity index decreases drastically in the range of cement content of up to about 7% at which the plasticity index starts to increase with the increase of the cement content.

The initial decrease in water holding capacity of the soil (liquid and plastic limits) is attributed to the cation exchange process between the cations of the soil and those of the cement that suppresses the double layer thickness due to the increase in the cation concentration. This cation exchange process at small cement content is associated with minimal, if any, pozzolanic activities as indicated by the pH value, depicted in Fig. 4, which reflects the hydration of the lime content present in cement; the pozzolanic reaction is induced by the $Ca(OH)_2$ produced from the hydration process. Figure 4 shows that the pH value of clay-cement mixture increases sharply at small cement contents and reaches a value of

11.4 at a cement content of about 6%, after which the pH value becomes practically constant. Figure 4 also shows that the pH value of clay-cement mixture increases also with time. On the other hand, the increase in liquid limit for cement content of more than 6% is due to the increase in pozzolanic reaction attributed to the presence of high amount of $Ca(OH)_2$ as indicated by the large pH value for cement content greater than 6%. The pozzolanic reaction increases the water holding capacity of the soil and thus increases the liquid limit and plastic limit of the soil.

Effect of cement content on undrained shear strength obtained from UU tests

The results of the undrained shear strength obtained from UU triaxial compression tests for the untreated and treated samples are shown in Fig. 5 as a function of the cement content that ranges from 0 to 20% by dry weight of the soil. The undrained shear strength is taken herein as half the principal stress difference at failure defined earlier. Figure 5 shows that the undrained shear strength generally increases with the increase of the cement content. However, the relationship between the undrained shear strength and cement content can be divided into three segments depending on the rate of increase of the undrained strength with the cement content. The first segment is for cement content that ranges from 0 to 6% in which the increase in the undrained strength is very slow indicating that the pozzolanic reaction, which is responsible for the increase in the soil strength, is very small. The second segment is for cement content that ranges from 6 to 10 % in which the rate of increase in the undrained strength is largest indicating maximum rate of pozzolanic reaction, which is associated with relatively large pH value of the soil-cement mixture as shown in Fig. 4. The third segment is for cement content that ranges from 10 to 20% in which the rate of increase in the undrained strength on average is similar to that of the first segment. This observation supports the discussion with respect to the Atterberg limits in the sense that the cation exchange process is dominant at small cement content (less than 6% for the soil of the present study); whereas the pozzolanic process is dominant at larger cement content (greater than 6% but less than 10% for the soil of the present study).

Figure 5 shows that the addition of cement greater than 10 % does not justify the cost of the further addition of cement because the rate of increase in strength is small and may also be associated with an increase in the soil swell potential as shown in the next section.

Effect of storing period on undrained shear strength of cement-treated soil

In order to examine the effect of storing time on the undrained strength of the soil utilized in the present study, two sets of UU tests were conducted on identical specimens treated with 20 % cement and prepared at the same water content (15%) and same dry density (15 kN/m^3). The only difference between the two sets is the storing period before conducting the tests. The first set was tested immediately after the specimens were prepared whereas the second set was tested after 6 days from the preparation of the specimens. The results of these two sets of UU tests, depicted in Fig. 6, show that significant increase in the undrained strength was observed with the increase of the storing period. However, the rates of increase with cell pressure for both sets are similar specifically for cell pressure values greater than 150 kPa. The increase of undrained strength with time is associated with the increase in the pH value with time (Fig. 4) that reflects the increase in the pozzolanic reaction, which is responsible for the increase in the strength of the soil.

Effect of cement content on percent free swell

The percent free swell results obtained for the untreated and treated soil specimens are depicted in Fig. 7, which shows the variation of the percent free swell with cement content for specimens prepared at two different water contents of 15 and 17%. As can be seen from Figs. 3 and 7, the shapes of the curves representing the percent free swell versus cement content relationship resemble that of the plastic limit versus cement content relationship (for the soil utilized in the present study). As can be seen from Fig. 7, the percent free swell drastically decreases in the range of cement content from 0 to 4%; whereas it (the percent free swell) drastically increases in the range of cement content from 4 to 6% after which the percent free swell decreases again but more steadily than in the initial stage. Figure 7 shows that the use of cement content of 15% reduces the swell potential and also shows that the amount of this reduction depends on the initial water content; the specimen prepared at the higher water content shows a significant reduction as compared to that prepared at the lower water content.

Figure 7 shows that the shapes of the two percent free swell versus cement content curves are generally similar; however, the rate of decrease in the range of cement content from 0 to 4% is larger for the specimens prepared at the lower water content. Furthermore, Fig. 7 indicates that the reduction of swell potential due to addition of cement depends on the initial water content; for example, the minimum value of percent free swell at 4% cement is 0.50% for the specimen prepared at the initial water content of 17% whereas it is 2.35% for the specimen prepared at the initial water content of 15%.

Figure 7 shows also that the addition of cement (from 4% to 6%) caused significant increase in the swell potential particularly for the specimen prepared at an initial water content of 17% for which the swell potential was almost doubled as compared to that of the untreated specimen.

CONCLUSIONS

This investigation was carried out to assess the effect of cement treatment on the Atterberg limits, shear strength and swelling potential of highly expansive clay obtained from Al-Marj – Al-Karak - Jordan. A wide range of cement content varying from 0 to 25% by dry weight of soil was utilized in this study. The liquid limit of this soil initially shows a drastic reduction until the cement content reaches 6%, then followed by a drastic increase for a cement content in the range of 6 to 10%. However, the liquid limit becomes practically constant for a cement content greater than 10%.

The variations of the percent free swell with cement content are observed to be similar to those of the plastic limit with cement content. However, the free swell test results show a minimum value at a cement content of 4%; whereas the plastic limit exhibits a minimum value at a cement content of about 6%.

Generally, the undrained strength increases with the increase of cement content, but the rate of this increase varies depending on the range of the cement content. The maximum rate of increase in undrained strength of the soil utilized in this study was observed to be in the range of cement content from 6 to 10%; the maximum pH value was attained in this range of cement content indicating significant pozzolanic activities due to the presence of high concentration of $Ca(OH)_2$.

The significant reduction in liquid limit and the small rate of increase in undrained strength in the range of cement content from 0 to 6% indicate that the cation exchange is the dominant process in this range and the pozzolanic reaction, if any, is minimal. On the other hand, the significant increase in both liquid limit and undrained strength in the range of cement content from 6 to 10% indicates that the pozzolanic reaction is the dominant process in this range.

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