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Time and Soil Type Dependent Suction Change in Clods

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Abstract- The engineering behavior of a soil depends strongly on its structure. This is dependent on the micro scale soil properties, the clod sizes, the initial moisture condition of the clods, porosity and the moisture content of the compacted soil mass. As the soil gets drier and becomes unsaturated, there is a suction effect developed which is the difference between the air pressure and the pore water pressure in the soil. Suction is directly proportional to the shear strength of the soil. It is also affected by the degree of saturation of the soil, which is a function of the variations in the moisture contents over a period of time. Previous laboratory studies have shown noticeable behavioral differences in the compacted soil specimens when sampled at initial wet and dry conditions. These differences are obvious in the shear strength and volume change behaviors. Therefore, this study focuses on the moisture content changes in clods made from two selected soils having medium and high Plasticity Index (PI) values respectively. To achieve this, a procedure was developed to determine the moisture differentials and total suctions by evaluating the soils behavior in their drying cycles. Each of the soils was sampled in its initial moisture condition. From their initial moisture contents, the soil samples were pulverized into smaller particles to pass the number 40 sieve. Clods were made from each soil and brought to specific moisture contents which was studied at two different curing times (0 day and 14 days).The results from this study gave a correlation between the moisture contents and measured suctions. These have helped to understand the behavioral differences earlier observed in soils in terms of the shear strength and volume changes.

Keywords: moisture content, suction, clods, curing time, drying cycle, soil type

1. Introduction

It is believed that the ultimate shear strength and volume change behavior of soils are related to their initial moisture conditions and the suction in the clods (Cerato et al., 2009). The suction is expected to increase from the external parts to the interior of the clods as they dry out during a drying cycle. Furthermore, highly plastic soils are expected to develop a higher suction based on the fabric and structure of the soil clods.

This paper focuses on the study of the change in moisture contents and suction in clods made from two soils collected from two different construction sites in Oklahoma. The goals of this study are to have a better understanding of soils and rocks in terms of their strength and volume change behaviors and their relationship with the initial moisture conditions. The objectives of this study are to determine the water front as the clods dry out for the 0-day and 14-day curing times and analyze the plots showing moisture contents as a function of time, measurement of the suction as the clods dry out for both curing times and the comparison of the results for each soil and their relationship with the previously drawn conclusions from their engineering behaviors.

The results obtained provides adequate insight into the behavior of the soils which helps engineers to analyze settlements, heave and shrinkage and make accurate predictions that are useful for the design of foundations and the structures which will be built on them.

2. Background study

Soil is referred to as a particulate system and is composed of discrete mineral particles (Lambe, 1958). It is generally made up of three constituents known as solid, liquid and air phases. The solid phase is composed of mineral aggregates which defines the soil skeleton while the air and liquid phases make up the 'voids' in soil. In a saturated soil, the air void is totally filled with water. In unsaturated soils, there exists a fourth phase identified by Fredlund and Morgernstern (1977) as the air–water interface, otherwise known as contractile skin. In terms of the weight or mass relationship, the most valuable parameter that represents the state of the soil is known as moisture content (Lambe, 1958). The moisture content (w) is defined as the ratio of the weight of water to the weight of solid particles in a soil.

The structure of a soil plays a very important role in the evaluation of its engineering behavior (Barden et al., 1969; Barden and Sides, 1970; Booth, 1975; DiBernardo and Lovell, 1980; Benson and Daniel, 1990; Lawton et al., 1992; Cerato et al., 2009). The structure of a soil relates to the arrangement of the soil particles and moisture movement through the pores within the fabric (Lambe, 1958). The soil fabric is the geometric arrangement of particles. Soil structure is also a function of the clod size and pore size distribution (Miller and Cleomene, 2007). Li and Zhang (2009) and Koliji *et al.* (2010) proposed that inter-aggregate pores and intra-aggregate pores exist within unsaturated soil samples when compacted. These pores greatly influence the ultimate shear strength and volume changes observed in soils when loaded.

The air and water phases which make up the soil voids in an unsaturated soil generate two pore pressures, namely: pore air pressure u_a and pore water pressure u_w. The intermolecular forces acting on the molecules in the contractile skin result in a tensile pull along the interiors of the liquid surface. This pull is referred to as surface tension and it is described as the force per unit length acting on the air-liquid interface. The effect of surface tension causes the pore air pressure to be higher than the pore water pressure. Schofield (1935) defined soil suction as 'pressure deficiency' in the pore liquid that exists in a saturated and unsaturated soil. In an unsaturated soil that has a continuous air phase, the pore air pressure is often found to be equal to the atmospheric pressure and the value of the pore water pressure is negative, relative to the air pressure. The term 'total soil suction' is divided into two components; matric suction and osmotic suction.

Clod is defined as a 'lump' or 'chunk' of soil which is formed as a result of the compaction of soil at water content lower than the optimum value. The clod structure begins to occur as a result of the aggregation of the soil fabric. Leroueil et al. (2002) further explained that this clod structure also depends heavily on the high clay fraction content of the soil. The increased plasticity of a soil is also a function of the high clay fraction content. When load is applied, the behavior of the soil fabric depends on the presence of the clod structure which appears stiffer and more pronounced at low moisture content (Whang et al. 2004). Miller and Cleomene (2007) studied the effect of soil structure on 1-D behavior using oedometer tests on soils of varying amounts of plasticity. It was observed that there were differences in the behavior of soils prepared at the same moisture content and dry density values, but at different maximum clod sizes. Cerato et al. (2009) also investigated the influence of clod size and soil structure on the wetting-induced volume change of compacted soil. In the study, 1-D compression and wetting tests were carried out to determine the effect of the variations of clod-size on the volume change behavior of soil. It was observed that the influence of soil structure depends on the soil type and the nature of clods. Clayey soils were found to be more susceptible to the influence of soil structure on volume change behavior due to the potential for substantial development of clod structure in them. On the other hand, silts and clayey sands with lower plasticity did not appear to experience considerable structure effect in the 1-D oedometer tests. Furthermore, the initial moisture condition within and between the clods and the pore size distribution due to the arrangement of the different clod sizes were observed to be major factors that contributes to the collapse potential and swell index of the soil.

Several laboratory methods have been adopted to measure the amount of suction in soils which include the use of thermal conductivity sensors, tensiometers, chilled mirror hygrometers, filter paper test method, WP4 water potential meter and PST-55 psychrometer. Since each of this equipment has a range of suction values it can measure, an appropriate selection of the right method and equipment to adopt depends on the range of values of suction expected from the soil to be tested. A highly expansive clay soil is expected to develop high suction as it becomes drier, and the use of WP4 potentiometer and PST-55 psychrometer will be more appropriate. The WP4 potentiometer is made up of a sealed block chamber which has a sample cup, a dew point sensor, a temperature sensor, a fan, a mirror, a fan and an infrared thermometer. The sample cup is filled with the soil sample and the equipment is set to bring the content of sample cup to equilibrium with the air in the sealed block chamber. When the equilibrium condition is reached, the suction equals the water potential of the air in the chamber (Esmaili et al., 2014). The WP4 equipment measures the amount of suction up to 300 MPa. The amount of time it takes to equilibrate is just a few minutes and it is highly preferred because of the accuracy in its estimation of soil suction.

3. Method

This section describes the selected soils for this study and the method adopted in the preparation of the clods. It also shows the procedural steps and equipment used in the determination of the moisture contents and suction changes over a period of time.

3. 1. Test Soils

Two soils of different plasticity index values; namely Kirkland and Pawhuska and Hollywood soils were selected. The samples used were taken from previously collected soils from different construction sites in Oklahoma. The selected soils were of medium and high PI values respectively. The standard classification with the physical and engineering properties of the identified soils are as shown in Tables 1 and 2 (Cerato et al., 2009). Powder X-ray diffraction analyses were performed on both soils to determine their mineralogy. The minerals found in Kirkland and Pawhuska soil include Chlorites, quartz, kaolinites, illites and feldspar; while Hollywood soil is made up of smectites, illites, quartz, kaolinites, feldspar and mixed layers of illite –smectites (Fadipe *et al*, 2015).

3. 2. Experimental Procedures

Sample preparation

The two soils were left to dry out in a pan to ensure an equilibrium in their initial moisture contents. For each soil type, the dried chunks were pulverized into smaller particles with a mortar and pestle. About 4000 g of the soil that passes through the number 40 sieve was used to prepare the samples for the dry analyses. The analyses represent the drying cycles of each soil after water was added to it.

Table 1: General Characteristics of Test Soils (Cerato et al., 2009)

Soil No.	Soil name	General Characteristics	Soil Location
1	Hollywood	Yellowish Olive	Rt. US 70, St. Rt. 7, Idabel, Mc Curtain County, OK
2	Kirkland and Pawhuska	Brown, residual soil	I-35/ Robinson, Norman, Cleveland County, OK

Table 2: Properties of Test Soils (Cerato et al., 2009)

Soil No.	Specific gravity	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Clay Fraction (%)

1	2.78	65	22	43	61.5
2	2.74	44	18	26	38

Preparation of clods

From the fine sample passing through the number 40 sieve for each soil, the initial moisture content of the dry soil was determined. This is to estimate the amount of water that will be added to bring the sample to a wet state and a moisture content value that is slightly higher than the pre-determined plastic limits. The estimated amount of water was added. The Kirkland and Pawhuska soil was made up to about 26% moisture content and the Hollywood soil was made to about 36%. Clods of approximately 38mm were hand made from each of the soils to equal weights. Figure 1 (a - b) shows the hand-made clods. The clods were divided into two portions. One portion was kept in a sealed polythene bag (as shown in Figure 1 (b)) and kept in a humid room to cure for 14-days before air drying while the other portion of clods was left to dry out immediately (0-day curing). To ensure accuracy, the drying procedure was done by placing the clods on a flat pan and rolling each of the clods at intervals to dry uniformly across the entire spherical surface.

Air drying the clods

The 0-day and 14-days cured soil clods were placed in a pan and left to dry out naturally in a controlled room. The values of the room temperature and relative humidity at the time of measurements were monitored using the wired indoor/outdoor thermometer and hygrometer device and their values were in the range 71-73 ^{o}F and 31-34% respectively.

Fig. 1 (a). Hand-made clods

Fig. 1 (b). Clods kept in a bag for 14 days

Measurement of moisture contents and total suctions

The moisture change with respect to time was measured as the clods dried out. Before cutting the clod into layers, the weight of each clod selected for evaluation was weighed. The moisture content was determined with reference to the dry weight of the representative oven-dried clod for each soil respectively. Each clod selected was then cut into three layers to determine the moisture contents from the exterior surface to the interior parts of the clod and the wetting fronts was observed in the drying cycle. The outer, intermediate and inner layers of the clods were examined using the profile shown in Figure 2. The moisture contents of the layers were determined by weighing the slices in moisture content tins on a weighing balance. This was done immediately after each representative was collected and after each tin had been oven dried for 24 hours. The moisture content differential was calculated using Equation 1:

$$moisture\ content\ (\%) = \frac{weight\ of\ water}{weight\ of\ dry\ soil} * 100\% \quad (1)$$

The total suction measurements were carried out using the WP4 potentiometer. Before measurements were taken, the WP4 potentiometer was calibrated for accurate results. Each slice had a representative sample of the outer, inner, and the middle layers; and was placed in suction cups to measure the suction values.

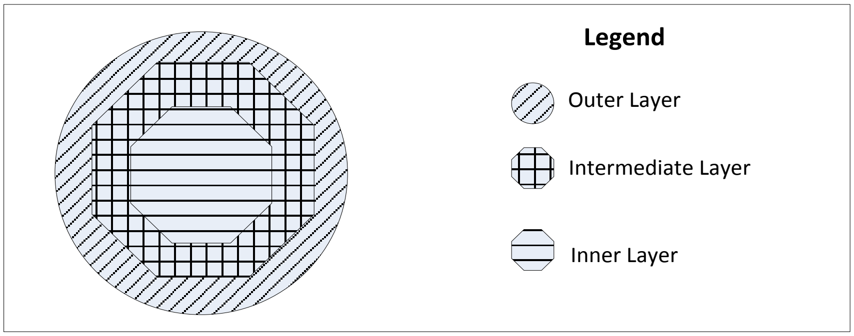

Fig. 2. Profile for cutting the soil clod

4. Results and Discussion

This section presents and discusses the experimental results obtained from the moisture content and suction tests carried out on the studied soils. The results provide an explanation of the engineering behaviors earlier observed from previous studies done on the soils.

4. 1. Analyses of Results

Plots showing the moisture content as a function of time were made to study the movement of water through the layers of the Hollywood and Kirkland and Pawhuska soil clods as shown in Figures 3 – 4 and 8 – 9 respectively. Likewise, plots of measured suction as a function of time were made to study the suction changes in the layers of the Hollywood and Kirkland and Pawhuska soil clods as shown in Figures 5 – 6 and 10 – 11 respectively. In addition, the determined moisture contents of whole clods sampled before they were cut into layers were plotted as a function of time to see the general moisture behavior of both soils as shown in Figures 7 and 12 respectively. The results were analyzed for the drying cycle of the soils and are expected to provide a correlation between the moisture contents and measured suctions for both curing times.

4. 2. Discussion

From the results of the study, the general behavior of most clods sampled from both soils shows that the soils clods get dry from the outside layer into the interior parts of the clods over time. In both soils, the amount of moisture in the inner layer is higher than the intermediate and outer layer of the clods for both curing times. This is also validated by the higher value of suction in the outer layers when compared to the intermediate and inner layers for both soils as shown in Figures 5-6 and 10-11 for the Hollywood and Kirkland and Pawhuska soils respectively. There is an exceptional observation of higher suction values in the intermediate layers of the clods from both soils at different curing times. This can be related to the equilibrating effect on the intermediate layer due to the internal movement of moisture in the outer and inner layers of the clods which occurs over a period of time. Also, the plots of the moisture content as a function of time within the profiled layers of the clods show that the drying rate of the soils vary between the layers and the initial curing condition has an influence on this behavior.

In the Hollywood soil plots shown in Figures 3 and 4, the 0-day clods' curves differs from the 14-days curve in terms of the combined trend of all of the layers. The drying rate appears to be faster in the 0 – day curing curve. The difference in the amount of moisture loss is about 7% higher in the 0-day clods when compared to the 14-day test clods at 120 hours from the start of measurement. This is because the soil holds more water due to the longer curing time and the pores are filled with more water which would not make it easily permissible for dry air to flow in. The suction plots for the 0-day and 14-days curing curves in Figures 5 and 6 show that suction increases at a faster rate earlier 0-day clods than in 14 days clods. The values of suction for the 0-day clods started to increase considerably at about 35 hours while it took about 55 hours for the 14-days clods to show a considerable increment. This can also be explained by the residency period of water in the voids of the soil clods during the curing time.

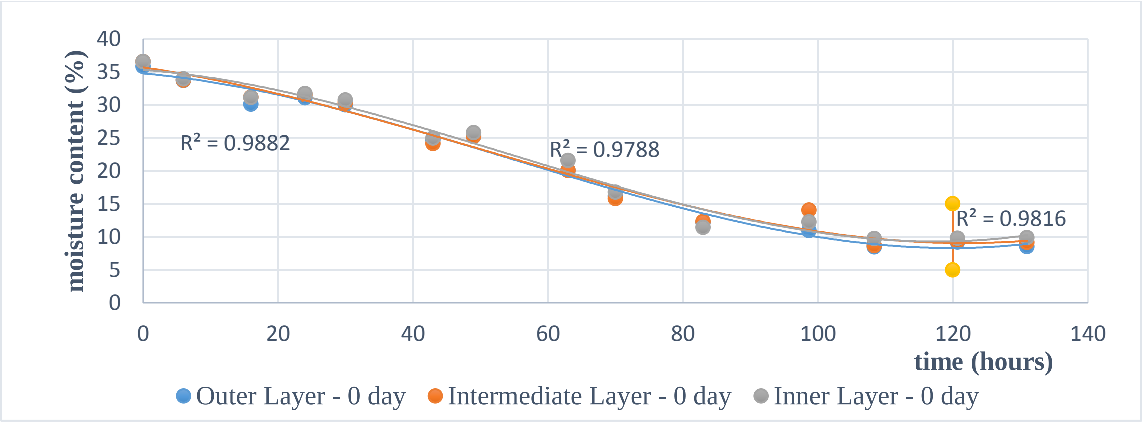

Fig. 3. Plot of moisture content versus time in layers of Hollywood clods (0 - day)

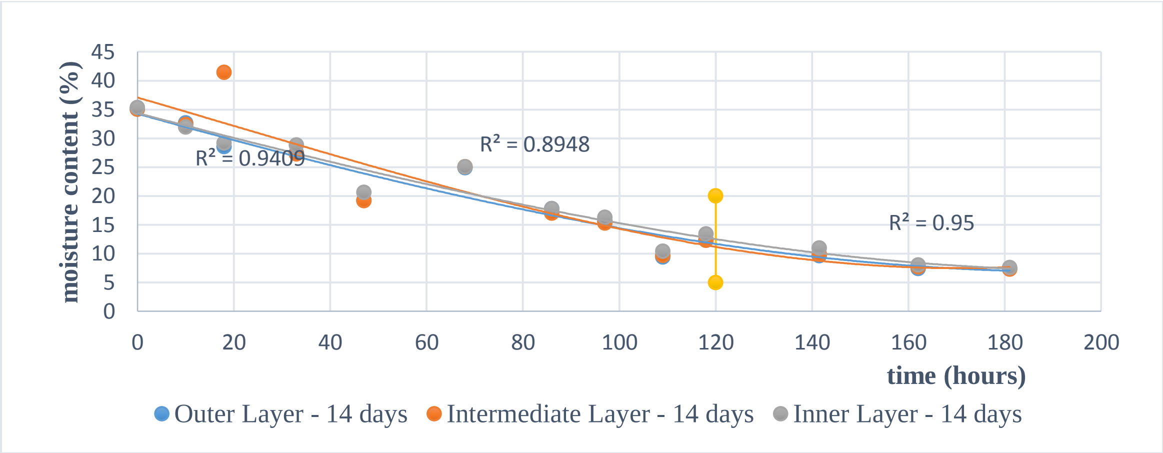

Fig. 4. Plot of moisture content versus time in layers of Hollywood clods (14 - days)

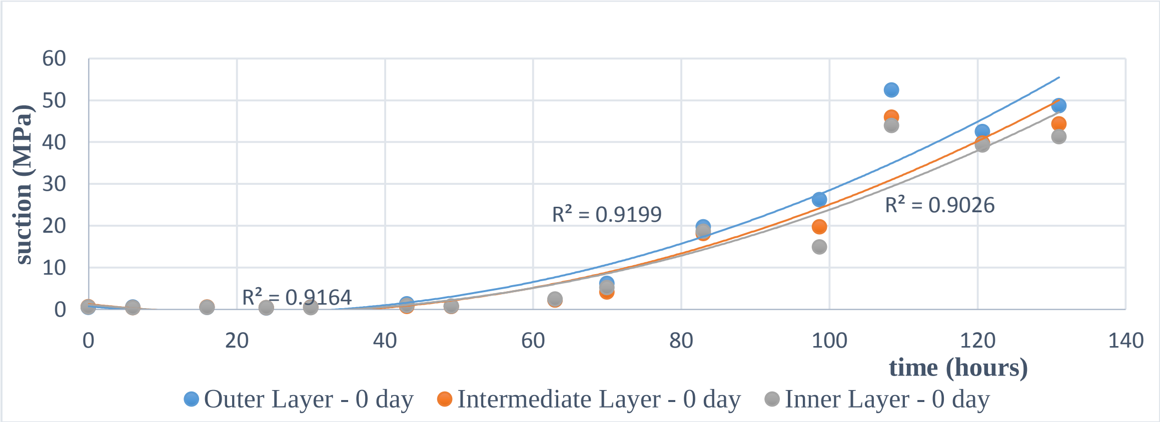

Fig. 5. Plot of suction versus time in layers of Hollywood soil clods (0 - day)

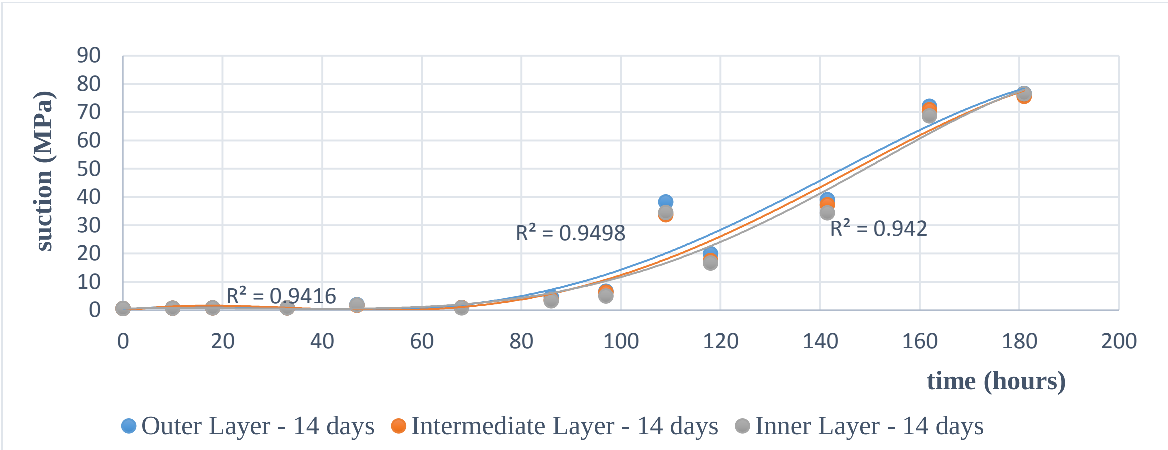

Fig. 6. Plot of suction versus time in layers of Hollywood soil clods (14 - days)

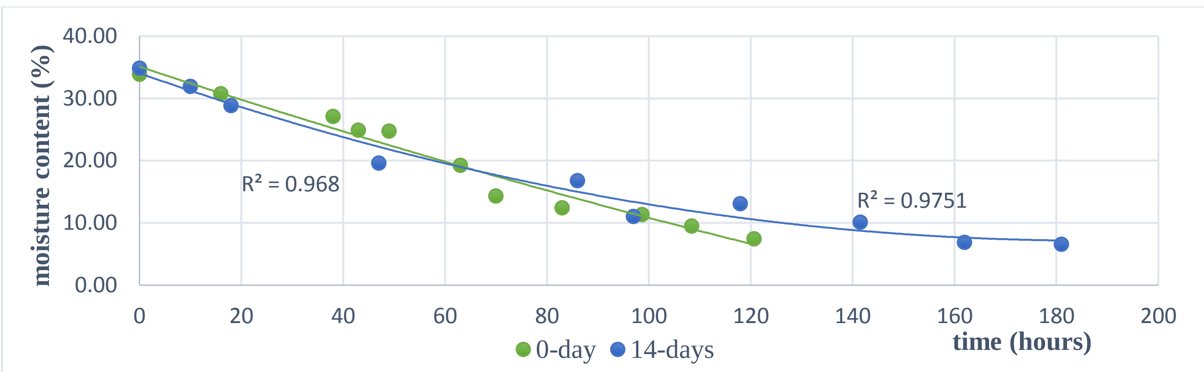

Fig. 7. Plot of moisture contents versus time in full clods of Hollywood soil

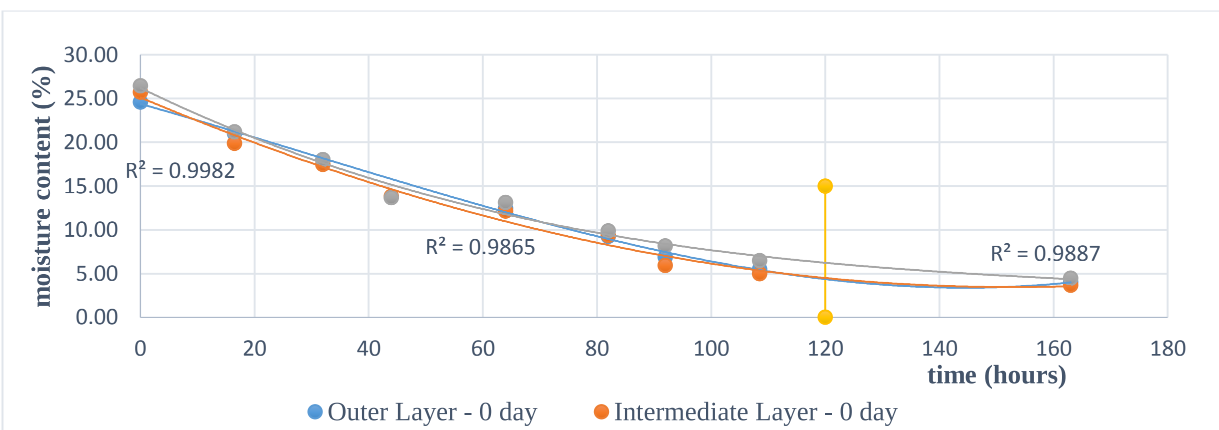

Fig. 8. Plot of moisture content versus time in layers of Kirkland and Pawhuska soil clods (0 - day)

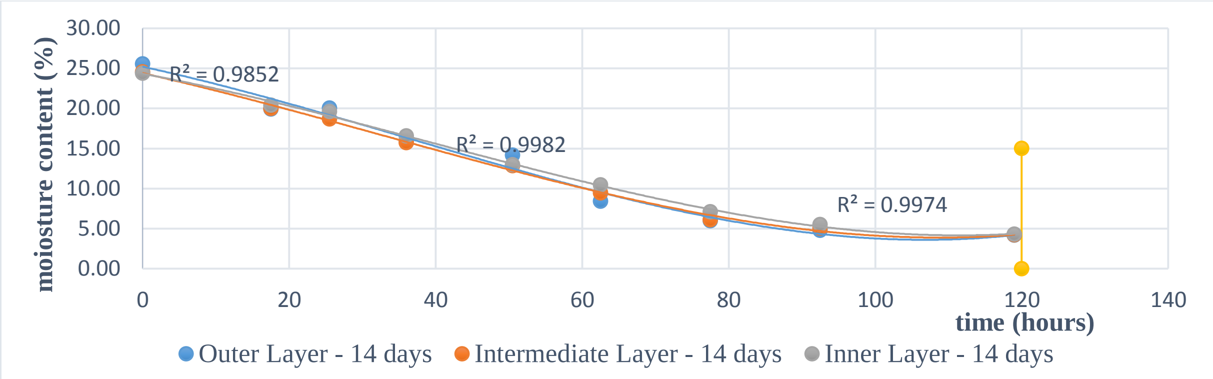

Fig. 9. Plot of moisture content versus time in layers of Kirkland and Pawhuska soil clods
(14 -days)

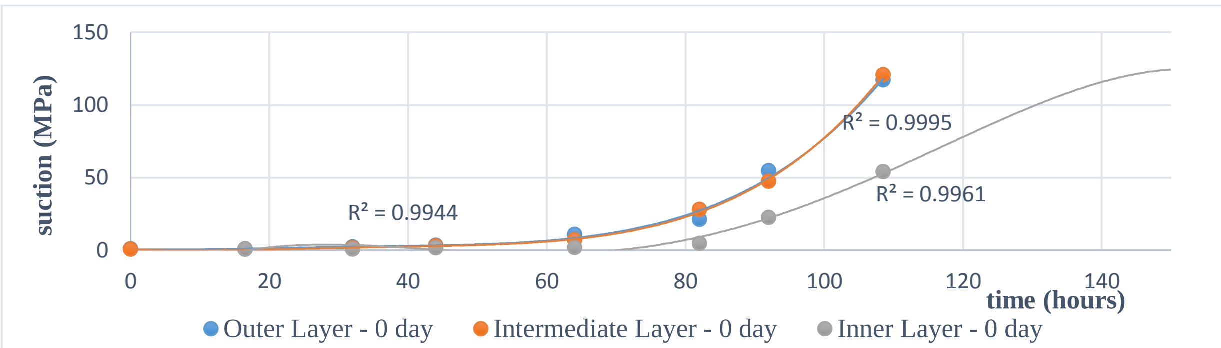

Fig. 10. Plot of suction versus time in layers of Kirkland and Pawhuska soil clods
(0 - day)

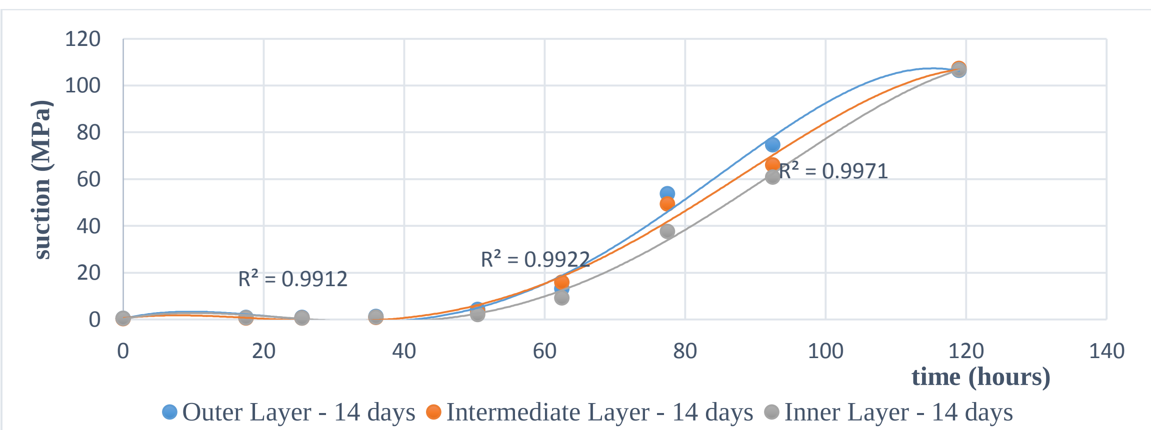

Fig. 11. Plot of suction versus time in layers of Kirkland and Pawhuska clods (14 - days)

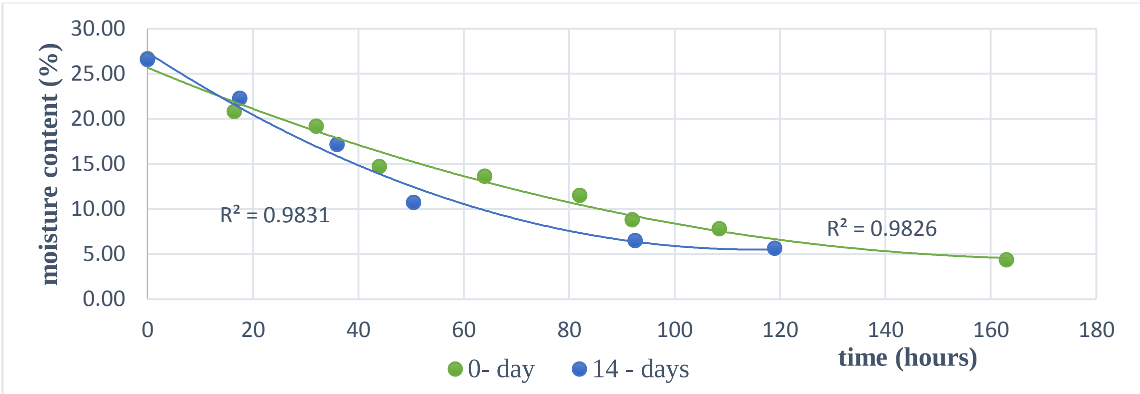

Fig. 12. Plot of moisture contents versus time in full clods of Kirkland and Pawhuska soil

The chemistry between soil particles and the water molecules causes a bonding in the soil layers and it tends to hold water for a long time. The pressure generated by the water in the clod requires longer time before it can be overcome by the dry air pressure entering into the clod. There is a significant variation in the suction values of the layers as the Hollywood clods dry out in the 0-day results in Figure 5; while in the 14-days test results shown in Figure 6, the suction values in the three layers appears to converge as the layers dry out at a more uniform rate. Figure 7 shows that it takes a longer number of hours for the 14-days cured sample to dry out when compared with the 0-day curing sample. It initially appears that there is a higher amount of moisture present in the 0-day clods than the 14-days clods until after about 63 hours, but after equilibrium is reached, the 14-days clods retain more water and dry out in a uniform and homogeneous manner.

On the other hand, the 0-day and 14-days curves of Kirkland and Pawhuska soil in Figures 8 and 9 describes the water holding capacity of the inner layer before it started drying out as compared to the outer and intermediate layers. Figure 8 shows that contrary to the observations in the Hollywood soils, layers of the Kirkland and Pawhuska soil dry out faster when it had been through a curing time of 14-days than when it is 0-day cured. At about 100 hours, the amount of the moisture content of the layers with respect to the curing times is about 3% higher in the Kirkland and Pawhuska soil as determined from Figure 8 and 9. The plots of suction versus time shown in Figures 10 and 11 validate the moisture contents curves for both curing times. The inner layer has a lower value of suction relative to the outer and intermediate layers. As expected based on the plots in Figures 8 and 9, the outer layer has higher suctions based on the direction of drying from the exterior parts of the clod into the core. The suction increases significantly in the outer layer after 20 hours but did not start increasing in the inner layer until about 60 hours. After many hours, the variation on suction values between the inner layer and other layers increases. Figure 12 shows the rate of decrease in moisture contents in the clods relative to the curing times. The 14-days clods dry out faster than the 0-day clods. The higher moisture content of the 14-days clod up till about 15 hours could be traced to the effect of the moisture vapor on the polythene bag on the clods surfaces during curing. The type of the soil and the engineering properties of the soil determine the moisture movement in the soil as shown in this study.

5. Conclusions

From the study, the following conclusions were drawn:

1. The behavior of soil is a function of its initial moisture conditions, soil structure, pore size and grain size distribution.
2. Internal moisture changes do occur in soils and the behavior per layer differs. The interlayer relationship of the moisture content can help to predict its overall behavior.

3. The moisture and suction changes in clods is a function of the soil type. Different soils are assumed to behave differently. Their plasticity indices amidst other properties can be useful in their behavior evaluations.
4. The overall behavior of soils is a function of its water retention time. The curing time determines the moisture changes and thus the suction effects.
5. Knowing the time function of the moisture and suction changes in soil clods are very useful in prediction of the soil behavior; however, the results of the interlayer moisture movement might not be sufficient to predict the engineering behaviors.

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