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Effect of Treated Waste Water on the Behavior of Unsaturated Soil

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Abstract: Many tests have been carried out on Karak clay to explore the unsaturated shear strength and volume change characteristics. The specimens have been prepared with and without treated contaminated water. A specific experimental programme has been planned and completed on a range of degree of saturation. The shear strength test and swelling test results with distilled water have been compared with the presence of contamination in Karak clay. The test results show that there is not too much difference between the unsaturated shear strength tests on specimens without and with contaminated water in Karak clay. Also, the use of treated water will not increase or decrease the swelling. The results obtained from this study are expected to be of benefit and practical use for carrying out stability analysis of structures like embankments and foundations supported by clay particularly in a country that suffers from water shortage like Jordan. However, experimental evidence to support this study is still limited.

Key words: Shear strength, unsaturated soils, degree of saturation, treated contaminated water

Introduction

Unsaturated soil mechanics plays a significant role in the practice of Geotechnical and geoenvironmental engineering. The vast majority of civil infrastructure systems are founded on and in soils above the groundwater table where pore-water pressures are negative particularly in arid and semi arid regions. The solution to a large number of contaminant transport problems depends on an understanding of surface flow boundary conditions and the movement of fluids through the unsaturated zone where soils have negative pore water pressures. Rational unified approaches for dealing with unsaturated soils have recently emerged, providing the Geotechnical engineer with enhanced tools for dealing with the challenges of unsaturated soils.

Jordan is considered a semi arid region with a serious shortage problem of drinking water. Previous researches emphasized the possibility of reusing treated water in irrigation in Jordan as a solution for the shortage of water. This leads to the use of treated water for irrigation of trees around the cities and house gardens. However, Jiries (2001) found that the wastewater quality from Mutah university treatment plant (MUTP) is suitable for irrigation purposes in terms of salinity and its chemical parameters especially sodium content. Reusing treated water helps in mitigating the problem of water crises in Jordan. On the other hand, it participates in producing a large part of food and increasing the income of farmers without any negative effect on the environment.

The main purpose of the current research is to explore the effect of treated water on soil strength and swelling pressure. The treated water can be of great benefit to be used for compaction in roads and embankment. Furthermore, when it is used for irrigation, it will not affect the shear strength and swelling beneath the footing. This may contribute in solving the problem of shortage of water in Jordan. For these reasons, it is important to explore the shear strength and swelling pressure when it is mixed with treated water. As the soil in Jordan is unsaturated due to long summer, the second purpose of the present paper is to evaluate the effect of changing in water content of the soil with and without contamination on the shear strength of unsaturated soil.

The behavior of unsaturated soil is presented here in terms of degree of saturation rather than suction because the suction measurement is costly, needs high expertise and is time consuming. The treated water, which is investigated in the current paper, comes from MUTP. Many tests are carried out to investigate the properties of treated water. The results show that the treated water is within the safe limit, has no health hazards and has no noticeable effect on shear strength.

Unsaturated soil behavior

For saturated soils, the effective stress equation that was suggested by Terzaghi (1936), is given by

$$\sigma' = \sigma - u_w \tag{1}$$

Jennings and Burland (1962) and Burland (1965), defined the effective stress which was suggested by Terzaghi, in two propositions

- The effective stress σ\` in a soil is defined as the excess of the total applied stress σ over the pore pressure u.
- Changes in volume change and shearing strength of a soil are due to exclusively to changes in effective stress σ\`.

Terzaghi's effective stress equation for a saturated soil is first examined and the approach extended to determine the enthalpy associated with the air, water and solid phases and the interactions between the phases, in an unsaturated soil. The difference between the total stress and pore water pressure fully defines the state of stress and thus determines the shear strength or volume change response.

In the case of unsaturated soils, early research attempted to extend Equation (1). One of the most widely studied forms was proposed by Bishop (1959):

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \tag{2}$$

The isotropic stress state in an unsaturated soil is generally described by three measurable stress variables: the mean total stress, the pore air pressure and the pore water pressure. Constitutive models of unsaturated soils presented so far have been developed on the basic assumption that only two of these variables are actually independent. As a consequence, the experimental data based on the axis translation technique have been extrapolated to real conditions, where the pore air pressure is atmospheric and the pore water pressure is negative.

In order to describe the effective stress in unsaturated soil in a single equation, the following requirements should be satisfied:

- It should satisfy the dry case when the pore contains air only and the fully saturated case when the pores contain water only.
- The behavior of shear strength and volume change, collapse and swelling, of soil element subjected to a change in stress should be predictable in terms of effective stress and should be independent of the manner in which the total stress and pore air and water pressure change
- The effective stress should be verified experimentally

Bishop equation's is not able to predict the volume change behavior and the parameter χ could not be easily obtained, particularly for volume change. Also, it is clear that any criticisms of the effective stress or the parameter χ have proved to be more significant to the volume change behavior than shear strength behavior. This is may be for several reasons, which the volume changes, collapse and swelling, in unsaturated soil is more significant than the shear strength. Another reason may be due to the observation of the volume change during all the increment whereas the shear strength is considered at one stage.

However, Equation (2) does not correctly define the state of stress because it links two stress variables $(\sigma-u_w)$ and (u_a-u_w), with a constitutive parameter (Fredlund and Morgenstern, 1977). Fredlund and Rahardjo (1993) and Fredlund, ***et al.*** (1996) suggested an equation to predict the shear strength in unsaturated soil by using two independent stress variables to describe the behavior of the shear strength as follows:

$$\tau=(\sigma-u_a)\tan\phi'+(u_a-u_w)\tan\phi^b \qquad (3)$$

where

τ	is the shear strength.
u_a	is the pore air pressure.
u_w	is the pore water pressure.
(u_a-u_w)	is the matrix suction.
χ	is the contribution of the suction to the effective stress.
ϕ'	is the effective friction angle.
ϕ^b	is the angle indicating the rate of increase in shear strength relative to a change in matrix suction, (u_a-u_w) when using (σ_n-u_a) and (u_a-u_w) as the two state variables.

Escario ***et al.*** (1989), Fredlund ***et al.*** (1995) showed that the shear strength increases non-linearly with suction and the angle of friction with respect to suction decreases with increasing suction.

Critical state models for unsaturated soils have been proposed in recent years. An elasto-plastic critical state framework for unsaturated soils was formulated in a qualitative form by Alonso ***et al.*** (1987) and then developed in a mathematical way by Alonso ***et al.*** (1990). Wheeler and Sivakumar (1995) and Sivakumar and Wheeler (2000) proposed further modifications and presented some experimental work to support the elasto-plastic model. The models are defined in terms of four state variables, namely, mean net stress, deviator stress, suction and specific volume. However, the proposed models have been based on limited experimental data. Compacted specimens have generally been used for research and the complications of soil fabric resulting from the compaction procedures have brought difficulties into the interpretation of fundamental soil behavior (Wang ***et al.***, 2002).

Properties of treated water

Water, in general, always contains some type of impurity as a solid or gases state. The amount of such impurities determines where this water is going to be used. The wastewater was investigated only and then the wastewater mixed with the soil under question. For the purpose of comparison the soil was mixed with distilled water and then tested. All the result is presented in Table 1. Anions were analyzed by ion chromatography. Major cations were measured with flame photometer, the Electrical conductivity was measured by conductivity meter and pH was measured with pH meter. All the chemical parameters (HCO^{-}_{3}, CO_3^{-2}, Ca^{+2}, Mg^{+2}, K^{+}, Na^{+}, F^{-}, Cl^{-}, Br^{-}, NO_3^{-}, PO_4^{-3} and SO_4^{-2}) are within the range of wastewater quality according to WHO, Jordanian standard.

Materials and Methods

The soil used in the tests was silt-sandy with significant amount of clay, which is typical from the south of Karak. Results of standard Proctor compaction test on soil mixed with distilled and with treated water are shown in Fig. 1. Liquid and plastic limits are 40 and 20%, respectively. The specific gravity is of 2.7. The chosen dry unit weight was 1.6 gr cm^{-3} at moisture content of 8%, which is coincident with initial void ratio of 68%. The tests were conducted at room temperature. The surface tension for both kinds of water is the same and is equal of 0.0735 Nm^{-1}.

There is a need to undertake further laboratory research studies on unsaturated soils, particularly to obtain a fundamental understanding of the shear strength of unsaturated soils by testing soil specimens with simple soil structures. Three groups of tests have been conducted by using simple direct shear device. The first group was tested by using pure water and contaminated water on fully saturated test to obtain the effective angle of friction, ϕ', which is found 23°±0.5°. The results of consolidated drained (CD) tests show no differences in the angle of friction. The second group was carried out with different initial degrees of saturation (i.e. S_{ro} = 2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80 and 90) and constant normal stress, which is equal to 0.09 kg cm^{-2}. The third group was conducted at the same condition of second group but the normal stress is of 50 kg cm^{-2}. The same procedures were repeated by using contaminated water.

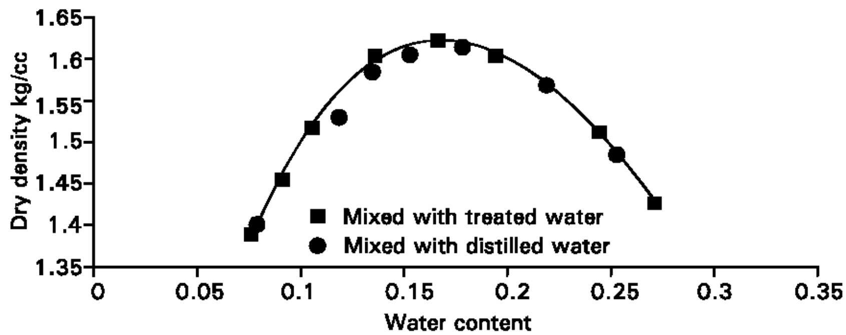

Fig. 1: Compaction test

Free swell test have been conducted by using odometer apparatus and at the end of each test the swell pressure was measured on soil mixed with distilled and with treated water. The tests were carried out with different initial degrees of saturation (i.e. S_{ro} = 15, 20, 25, 30, 35, 40, 50, 60, 70, 80 and 100)

Results and Discussion

Many drained direct shear tests were performed on unsaturated soil with and without contamination. The results of these tests show an increase in strength as the normal stress and degree of saturation increase. The stress strain behavior is nearly ductile for all the tests, with some strain softening taking place. Specimen has a similar influence on the stress-strain behavior and critical state characteristics as that of increasing its density through applying a higher normal pressure.

Table 1: Concentration of ionic and cation composition in ppm of treated wastewater

Parameter	Contaminated water only	Soil mixed with distilled water	Soil mixed with Treated water
HCO^{-}_{3}	261.24	48.123	302.49
Ca^{+2}	66.24	15.456	66.24
Mg^{+2}	26.82	6.71	34.88
E.C (in µS cm^{-1})	1100.00	60.3	1108.00
PH	7.08	7.73	8.00
K^{+}	23.60	4.4	26.80
Na^{+}	10.84	3.5	111.54
F^{-}	0.34	0.9203	0.48
Cl^{-}	84.39	1.7463	60.76
Br^{-}	0.82	Non-deductive	0.15
NO_3^{-}	28.06	0.08135	18.53
PO_4^{-3}	23.07	Non-deductive	20.64
SO_4^{-2}	65.86	1.3873	69.99

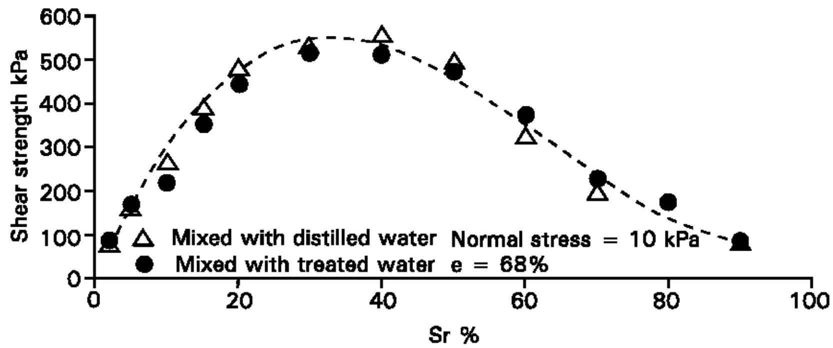

Fig. 2: Unsaturated shear strength versus degree of saturation

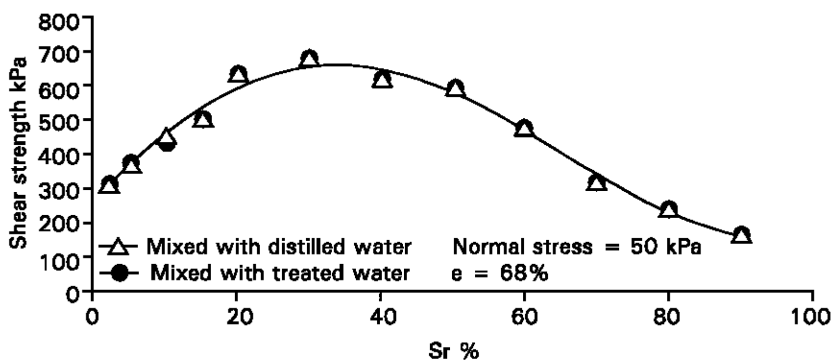

Fig. 3: Unsaturated shear strength versus degree of saturation

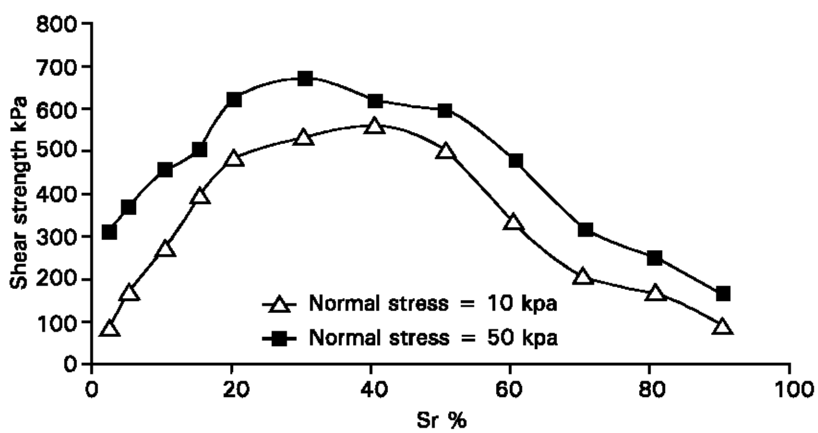

Fig. 4: Effect of normal stress on unsaturated shear strength

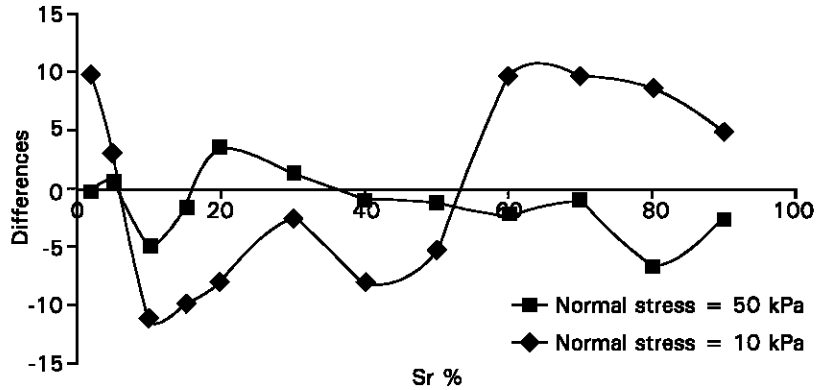

Fig. 5: Differences in the measured unsaturated shear strength for soil mixed with treated water and pure water at different normal stress

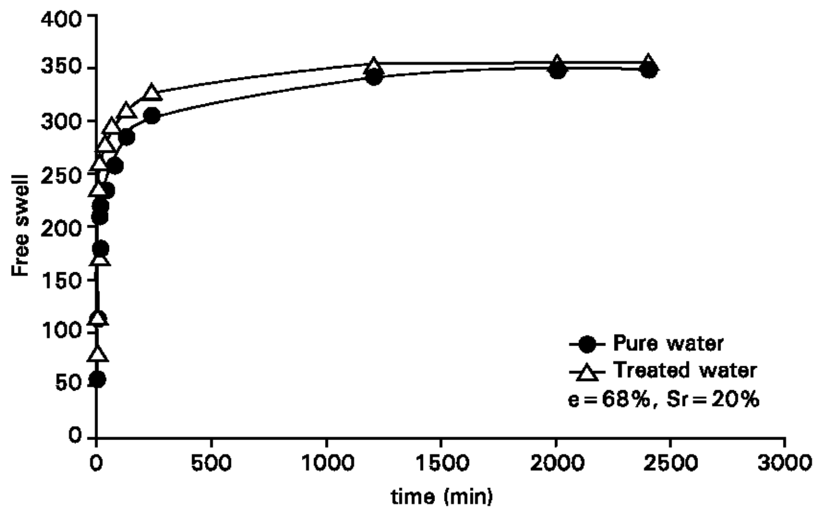

Fig. 6: Result of free swell tests

Samples could be prepared at a high saturation, in which the air is initially uniformly distributed, but this will be a temporary state and the case with which air can move through the pore spaces determines how long this temporary state will last. This means that the air in such a soil will tend to aggregate, so that the soil becomes separated into regions of full and low saturation. Therefore, the experiments here are conducted under drained conditions to avoid any kind of segregation. Also, this is the main reason for choosing simple direct shear test.

For low degrees of saturation and normal stress, the rise in pressure is very low and can be ignored. On the other hand, the rise in pore air pressure for high normal stress (i.e., greater than 100 kPa) should be considered if the test is undrained. In this paper, the pore pressure is atmospheric because it is drained direct shear.

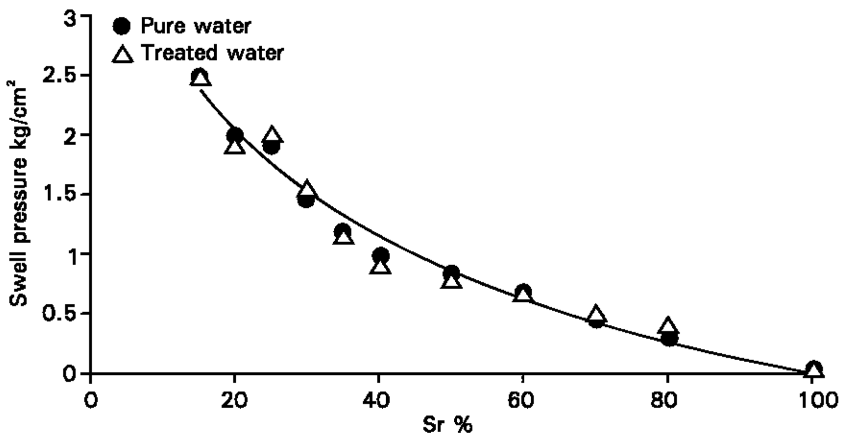

Fig. 7: Results of swell pressure tests

Fig. 1 confirms that using treated water has no effect on the result of compaction test. The water content for both kinds of water has not followed the same path due to repeatability of the test only. It can be concluded from Fig. 1 and Table 1 that the treated water has no effect on the compaction.

The relationship between the degree of saturation and shear strength for both soils that mixed with treated and distilled water show in Fig. 2 and 3. As the degree of saturation increases up to 25% the shear strength increases and then it becomes nearly constant between saturation 25 to 50%. In terms of suction, the shear strength increases as the suction increases and then decreases to a fairly constant value. This pattern is also seen in the results of other researchers (Donald, 1956, Towner ***et al.***, 1972 and Fredlund ***et al.***,1993). The shear strength may increase, decrease or stay constant as the suction increases beyond a certain value. As the saturation increases more than 60% the shear strength decreases.

Fig. 4 shows that as the normal stress increases the shear strength increases. Differences between the soils that were mixed with distilled and treated water (Fig. 1 and 2) are presented in Fig. 5. The maximum difference in shear strength values is around ±10% when the normal stress is of 50 kg cm^{-2} whereas is less than ±4% when the normal stress is of 10 kg cm^{-2}. However, the differences in initial void ratio and in initial degree of saturation among the samples are around ±2%. This means that the differences in shear strength could be due to differences in initial saturation, void ratio, instrument accuracy and repeatability of test.

The shear strength of unsaturated soil depends on its behavior on degree of saturation, number of contact or void ratio, surface tension and normal stress (Maaitah, 1999 and 2002). As the previous parameters have not changed in all tests, therefore the shear strength does not affect by using treated water or tape water. This result has been proved here.

Mixing soil with treated water has no effect on free swell and swell pressure as shown in Fig. 6 and 7. There are somewhat differences between which may be explained by the repeatability of tests. At low saturation the soil exhibits higher swell pressure as shown in Fig. 7. Also as the degree of saturation increases the swell pressure decreases. Then, as the degree of saturation increases the suction decreases and the swelling pressure decreases. The volume of change increases as the suction decreases and that the volume change became more significant at relatively low suction values (Escario and Saez, 1973). The soil swelling depending on various factors as the soil wetted under a constant pressure such as the degree of saturation (Cox, 1978).

It is clear that the degree of saturation and normal stress play an important role in determining the shear strength for unsaturated material. Important conclusion can be drawn from the experimental program that has been conducted in this research.

- Shear strength varies with the degree of saturation.
- Shear strength may be considered as a function of climate.
- Shear strength increases as saturation increases up to saturation range between 30 to 40% and decreases as saturation exceeds 60%.
- Shear strength increases as the normal stress increases.
- Treated water has no effect on soil shear strength.
- Treated water has no effect on compaction process.
- Treated water from MUTP is safe for using in earthwork.
- Treated water has no effect on free swell and swell pressure.
- Swell pressure increases as the degree of saturation decreases.

This research recommend using treated water from MUTP for civil engineering earthwork if it has no effect on volume change behavior. This conclusion will have a great benefit in solving water shortage in Jordan.

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References

Alonso, E.E., A. Gens and D.W. Hight, 1987. Special problem soils. General report. Proceedings 9th European Conference Soil Mech. Found. Eng., Dublin, 3: 1087-1146.

Alonso, E.E., A. Gens and A. Josa, 1990. A constitutive model for partially saturated soils. Géotechnique, 40: 405-430.

Bishop, A.W., 1959. The principle of effective stress. Lecture delivered in Oslo, Norway, in 1955; published in Teknisk Ukeblad, 106: 859-863.

Burland, J., 1965. Some aspect of the mechanical behaviour of partially saturated soils. Symposium equilibria and moisture changes in soils beneath covered areas. Ed. G.D. Aitchison. Soil mechanics section, CSIRO Australia. Butterworths, Australia, pp: 270-278.

Cox, D.W., 1978. Volume change of compacted clay till in Proc. ICE Conf. Clay Tills, pp: 79-86.

Donald, I.B., 1956. Shear strength measurement in unsaturated non-cohesive soils with negative pore pressure. Proceedings 2nd Australia New Zealand Conference Soil mech. Found. Eng. Christchurch, New Zealand, pp: 200-205.

Escario, V. and J. Saez, 1973. Measurement of the properties of swelling and collapsing soils under controlled suction. in Proc. 3rd Int. Conf. Expansive soils (Haifa), 1: 195-200.

Escario, V., J. Juca and M. Coppe, 1989. Strength and Deformation of partly saturated soils. in Proc. 12th Int. Conf. Soil. Mech. Found. Eng. (Rio de Janeiro, Brazil), pp: 43-46.

Fredlund, D.G. and N.R. Morgenstern, 1977. Stress state variables for unsaturated soils. Geotech. Eng. Divi., 477-465.

Fredlund, D.G. and H. Rahardjo, 1993 Soil mechanics for unsaturated soils. A Wiley-Interscience Publication, Johon Wiley andSons, INC.

Fredlund, D.G., S.K. Vanapalli, A. Xing, D. Pufah, 1995. Predicting the shear strength function for unsaturated soils using the soil-water characteristics curve. Proceedings of the 1st Int. Conf. on Unsaturated Soils Paris/ France.

Fredlund, D.G., A. Xing, M.D. Fredlund and S.L. Barbour, 1996. The relationship of the unsaturated shear strength to the soil-water characteristic curve. Canadian Geotech. J., 33: 440-448.

Jennings, J.E. and J.B. Burland, 1962. Limitation to the use of effective stress in partly saturated soils. Géotechnique, 7: 125-144.

Jiries, Anwar, G., 2001. Chemical evaluation of treated sewage effluents in Karak province and its suitability for irrigation purposes. Pak. J. Biol. Sci., pp: 4.

Maaitah, Omer, N., 1999 A Theoretical and Laboratory Investigation into the behavior of Unsaturated Soil. Unpublished Ph.D. Thesis, University of Bath, Department of Architecture and Civil Engineering, United Kingdom.

Maaitah, Omer, N., 2002. Shear strength at low degree of saturation-theoretical study Abhath Al-Yarmouk Journal, 11: 193-216.

Sivakumar, V. and S.J. Wheeler, 2000. Influence of compaction procedures on the mechanical behavior of an unsaturated compacted clay. Part 1. Géotechnique, 4: 359-368.

Terzaghi, K., 1936. The shear resistance of saturated soils. In Proc. 1st Int. Conf. Soil Mech. Found. Eng. (Cambridge, MA), 1: 54-56.

Towner, G.D. and E.C. Childs, 1972. The mechanical strength of unsaturated porous granular material. J. Agric. Sci., 23: 409-498.

Vanapalli, S.K., W.S. Sillers and M.D. Fredlund, 1998. The meaning and relevance of residual state to unsaturated soils. 51st Canadian Geotechnical Conference, Edmonton, Alberta.

Vanapalli, S.K., D.G. Fredlund, D.E. Pufahl and A.W. Clifton, 1996. Model for the prediction of shear strength with respect to soil suction. Canadian Geotech. J., 33: 379-392.

Wang, Q., D.E. Pufahl and D.G. Fredlund, 2002. A study of critical state on an unsaturated silty soil, Can. Geotech. J. Rev. Can. Geotech., 39: 213-218.

Wheeler, S.J. and V. Sivakumar, 1995. An elasto-plastic critical state framework for unsaturated soil. Géotechnique, 45: 35-53.