Swelling Behavior of Compacted Clay Soil from Elshrouq City, Egypt

Mohamed Elkinawy[1], Adel Gabr[1], Mohamed G. Arab[1] and Rafik Belarbi[2]

[1]Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura, Egypt
[2]LEPTIAB, University of La Rochelle, Avenue Michel Crépeau, 17042 La Rochelle, France

Abstract: Expansive soils are encountered in many regions in Egypt at the arid and semi-arid regions. This may cause severe damage of pavements, and light structures due to high to very high swelling potential and swelling pressures. This paper presents an experimental investigation of compacted expansive soil collected from Elshrouq, Egypt. This experimental investigation includes routine soil testing, several types of swelling testing using odometer device to determine the swelling pressure and swelling potential at various initial moisture content. Comparison between different test methodologies of measuring the swelling pressure of soil is performed. Moreover, shear strength of unsaturated swelling soil with varying initial matric suction is determined using the direct shear test. Finally, comparison between four different procedures to predict unsaturated swelling soil shear strength is conducted.

[Mohamed Elkinawy, Adel Gabr, Mohamed G. Arab and Rafik Belarbi. **Swelling Behavior of Compacted Clay Soil from Elshrouq City, Egypt.** *N Y Sci J* 2018;11(8):1-9]. ISSN 1554-0200 (print); ISSN 2375-723X (online). http://www.sciencepub.net/newyork. 1. doi:10.7537/marsnys110818.01.

Keywords: Swelling; Behavior; Compact; Clay Soil; Elshrouq City; Egypt

1. Introduction

Study of the swelling behavior of compacted expensive soil is a crucial in predicting the behavior of light weighted structures like pavements. Compacted swelling soils may be also used in dams and land fills, as a lining material due to it is low permeability. Moisture migration due to climatic conditions may change moisture content and matric suction of the compacted soil causing a change in volume and shear strength of the compacted swelling soils.

Several empirical methods have been proposed in the literature to predict the swelling properties of expansive soil using the soil classification parameters. These methods have been used extensively due to its simplicity (Vanapalli and Lu 2012). Recently, methods to predict the swelling properties of the swelling soils were extended to include more fundamental water potential parameters such as matric suction (Vanapalli and Lu 2012). However, these predictions may be limited to certain geological and soil formation used in these studies and may not reflect other soil formations.

To overcome this, several laboratory based methods have been used to predict the heave behavior of the swelling soils. Odometer based methods are used to predict the swelling properties of expansive soil using index parameters (i.e., swelling index (Cs and heave index Cp). Three testing methodologies have been used widely in the literature to predict the swelling index namely: Free swell (FS), Constant Volume test (CV) and Loaded Swell test (LS). Swelling pressure predicted from these methods varies due to the variation of the test method. Gilchrist (1963), Noble (1966) and Khaddaj et al. (1992)showed that the swelling pressure obtained from FS test is higher than obtained from CV test and LS test. While, Justo (1984) and Basma et al. (1995) mention that the swelling pressure from LS test is higher than the one obtained from CV test. However, Sridharan et al. (1986) show that the swelling pressure from CV test is higher than obtained from LS test.

Soil shear strength of unsaturated expansive soil is strongly depends on the value of initial moisture content. Several procedures have been proposed to estimate the soil shear strength using the soil water characteristic curve (SWCC) as a tool. The proposed model of Öberg and Sällfors (1997) predict the unsaturated soil shear strength based on the degree of saturation and matric suction of unsaturated soil. While Chenggang et al. (1998) proposed a different model to predict unsaturated soil shear strength based on the soil residual matric suction and air entry value. More models are summarized in (Garven and Vanapalli 2006).

The main scope of this research is to investigate the volume change and shear strength of compacted expansive soil collected from Elshrouq city, Egypt. This testing program includes investigation of the soil water retention and the effect of the retention characteristics on the volume and shear strength parameters. This study includes both routine testing for the investigated soil and volume and shear strength testing. Swelling pressure was determined using three different procedures namely: free swell test, loaded swell test and constant volume test. Comparison of the effect of the testing methodology on the measured swelling pressure is presented in this research. Also the effect of initial water content on the swelling potential is studied. Finally, the effect of the initial matric suction on the unsaturated swelling soil shear strength is investigated. A comparison between the different models to predict the shear strength of unsaturated soil is conducted based on test results.

2. Materials

Expansive soil samples were collected from Alshrouk city, New Cairo, Egypt. The soil samples were subjected to routine tests such as soil gradation, Atterberg limits, specific gravity and modified proctor test according to the American Society for Testing Materials (ASTM) specifications. The results of the routine testing and general engineering properties of the investigated soil are presented in Table 1.

Fig. 1 shows the soil gradation results and results of the hydrometer test conducted on the soil samples and the test was conducting according to (ASTM:D422 – 63 2007)According to the tests results, about 90% of soil passes through sieve No. 200, the clay percentage is about 52% and the liquid limit and plasticity index are 64.75 %, 44.34% respectively. The soil classification according to USCS is clay with high plasticity (CH).

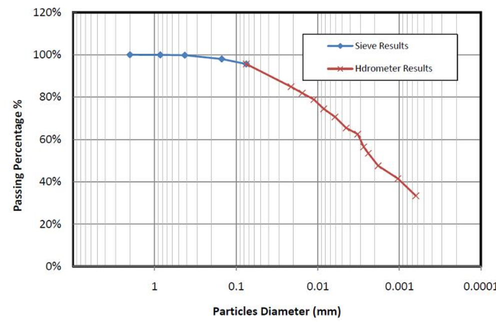


Fig. 1 Soil Gradation Based on Sieve Analysis Results and Hydrometer Test Results.

Table (1) Basic Properties of the Soil

	ASTM	Tested result
Liquid Limit	(ASTM:D4318 – 05 2005)	64.75%
Plastic Limit	(ASTM:D4318 – 05 2005)	20.41%
Plasticity index	(ASTM:D4318 – 05 2005)	44.34%
Clay Percentage %	(ASTM:D2487 – 06 2006)	52%
Activity	$A = \frac{[PI(\%)][\ ]}{\text{Clay percentage}(\%)}$	0.85
Classification according to USCS	(ASTM:D2487 – 06 2006)	CH
Classification according to AASHTO	AASHTO M145	A-7-6
Specific Gravity	(ASTM:D54-06 2010)	2.67
Maximum Dry Density	(ASTM:D1557 – 09 2011)	1.73 gm/cm^3
Optimum Water content	(ASTM:D1557 – 09 2011)	18%

Experimental Program

The experimental testing program included basic engineering soil tests, water retentions characteristics, free swell test, loaded swell test, constant volume test, swelling potential test and direct shear test for the collected swelling soil.

Swelling odometer testing

Swelling tests were performed using ConMatic IPC Auto-Consolidation HM-2470A.3Fat the Soil Mechanics and Foundation Engineering Laboratory, Mansoura University, Egypt. The device has a load cell and LVDT. The load cell with capacity of 10 kN and a resolution of 1 N. The LVDT has a range of 25 mm with a resolution of 0.001 mm. The device is connected to Data acquisition Unit (DAC) system and test results are recorded automatically on a personal computer controlled by DAC.

Free swell test.

The free swell test is performed according to (ASTM D4546 – 08 1996) Method A on compacted soil sample. The samples were tested at the optimum moisture content and the maximum dry density using modified proctor energy on a sample of diameter 50.8 mm and height of 19 mm. In the free swell test, the sample is subjected to a net vertical stress of 7 kPa and then inundated by water for approximately 48 hours to reach the maximum possible heave, then the vertical stress gradually increased till the axial strain reach to zero.

Loaded swell test.

The loaded swell test is performed according to (ASTM D4546 – 08 1996)Method B on four soil samples each sample was tested at different vertical stress (7, 50, 300 and 1000 kPa). The tests were performed on sample of diameter 50.8 mm and height of 19 mm. The samples initial moisture content and dry density was kept constant at optimum moisture content and maximum dry density. All the samples were inundated by water for 24 to 96 hour, and the axial vertical strain is recorded.

Constant volume test. The constant volume test is performed according to (ASTM D4546 – 08 1996) Method C. In this test soil was compacted at optimum moisture content and maximum dry density with dimensions of 50.8 mm in diameter and 19 mm height. The test was performed by applying a net vertical stress of 1kPa, the soil sample was inundated by water while increasing manually the vertical stress to prevent heave. After the heave is prevented due to the vertical stress, a routine consolidation test is performed according to (ASTM:DD2435 – 04 2010).

Swelling potential test. The swelling potential test is performed on compacted soil samples compacted at maximum dry density and three levels of the initial moisture content (OMC, OMC-5% and OMC+5%). The experiment was conducted on two of sample sizes to investigate the effect of the soil sample size on the measured swelling potential. Size 1 diameter is 50.8 mm and height of 19 mm while the size 2 diameter is 63.5 mm and height of 25 mm. The experiment was soil conducted by applying a net vertical stress of 7kPa and then the sample was inundated by water for 24 hours and the axial vertical strain was recorded.

Direct shear test.

Shearing tests were performed using the Pneumatic Direct Residual Shear HM-2560A.3Fat Soil Mechanics and Foundation Engineering Laboratory, Mansoura University, Egypt. The device has a horizontal load cell and vertical and horizontal LVDT. The load cell with capacity of 10 KN and a resolution of 1 N. The vertical LVDT has a range of 10 mm with a resolution of 0.001 mm. The horizontal LVDT has a range of 25 mm with a resolution of 0.001 mm. The normal stress is applied pneumatically on the soil sample. The device is connected to Data acquisition Unit (DAC) system and test results are recorded automatically on a personal computer controlled by DAC.

The soil shear parameters of the soil are determined by performing the direct shear test on compacted soil samples at the maximum dry density and six levels of initial moisture content. The sample size used has a diameter of 63.5 mm and height of 25.4 mm. Three levels of normal stress were used (100, 200 and 400 kPa). The applied horizontal rate of shearing is 0.20 mm/min.

Soil Retention tests

In order to investigate the effect of the water retention characteristics on the soil heave soil water characteristic curve (SWCC) for the tested soil was measured in the lab. SWCC is a relation between the soil degree of saturation and the matric suction; it is a very important tool when dealing with unsaturated soil. There are several methods to measure suction in laboratory among those filter paper method which is widely used indirect method to determine the soil suction. In this study samples compacted at the maximum dry density with different content were used. The compacted sample has a diameter of63.5 mm and height of 30 mm and divided into two parts with a flat smooth surface. The filter paper (Whatman No 42, 50 mm in diameter) then placed between the two soil sample parts until equilibration of the filter paper. To avoid any impurities stuck of the filter paper, the filter paper is inserted between two filter paper of diameter 6.35 cm. The sample parts are taped and encased on a closed container for one weak for equilibrium (Fig.2 shows test procedure). The wet and dry filter paper are measured by a scale of accuracy $=10^{-4}$ gm. The matric suction of the filter paper corresponding to its water content is determined according to the calibration curve provided by (ASTM:D5298 – 03 2003) as shown in Fig. 3.

Fig.2 Suction Test Steps

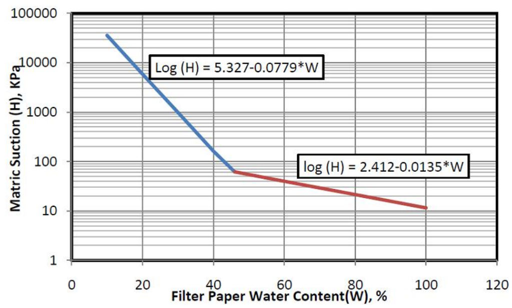


Fig.3 Filter Paper Whatman No. 42 Calibration Curve(ASTM:D5298 – 03 2003)

4. Results and Discussion

Free swell test

Test results for the FS test conducted on the soil sample at MMD and OMC is shown in Fig. 4, As shown in Fig.4, the maximum vertical strain after 48 hour is about 19% and the swelling pressure = 1000 kPa.

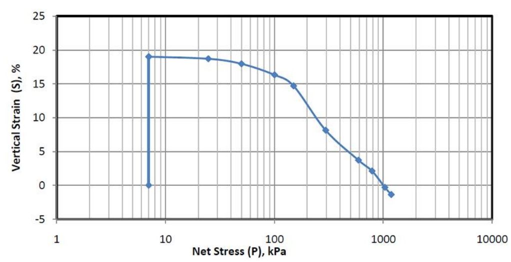


Fig.4 Free Swell Test Results

Loaded swell test

The loaded swell test is performed by applying the vertical stress and soil sample is inundated while keeping the vertical stress. The vertical stress is mainted during sample swelling and the vertical strain (s) versus time (t) is shown in Fig. 5. Rectangular hyperbola relationship can be fitted for the relationship between time and vertical strain as recommended by (Nagaraj et al. 2010). The rectangular hyperbola will have the form $S = \frac{t}{A + B*t}$. Where A is the intercepted part of (Y) axis and B is the slope of line fitted to the relationship between the time (t) and corresponding time divided by axial strain (t/s) shown in Fig. 6. The maximum vertical strain is $S = Lim_{X \to \infty} \frac{t}{A + Bt} = \frac{1}{B}$ according to (Nagaraj et al. 2010). According to Fig. (7) the swelling pressure is determined to be 1150 kPa.

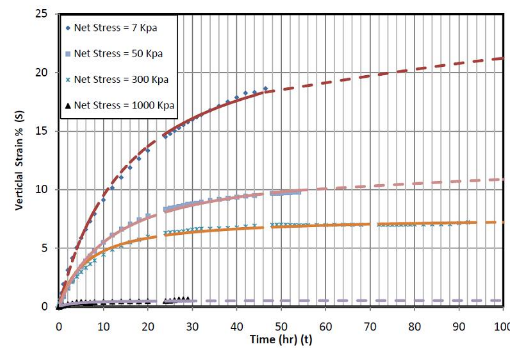


Fig.5 Time Versus Vertical Swell From the Loaded Lwell Test

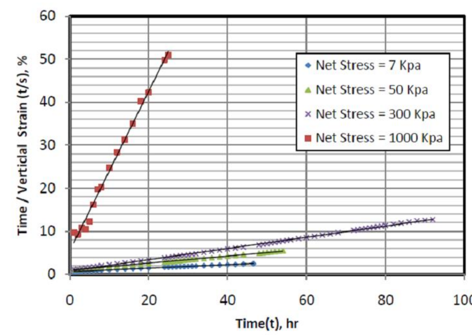


Fig. 6 Time/Vertical Swell Versus Time From The Loaded Swell Test

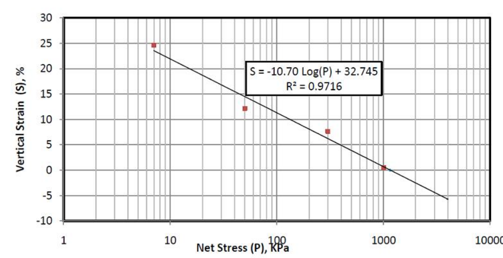


Fig. 7 Loaded Swell Test Results

Constant Volume test

The uncorrected swelling pressure is defined as the maximum vertical stress to prevent soil heave. The corrected swelling pressure is determined by Modified Fredlund et al. (1980) correction method, which a horizontal line and a tangent line are drawn at the point of maximum curvature. The corrected swell pressure is located at the intersection of the angle bisector of these two lines, and a line tangent to the curve and parallel to the rebound portion of the curve.

The test results show that the uncorrected swelling pressure is 201.3 kPa, the corrected swelling pressure according to Modified Fredlund et al. (1980) is 318 kPa.

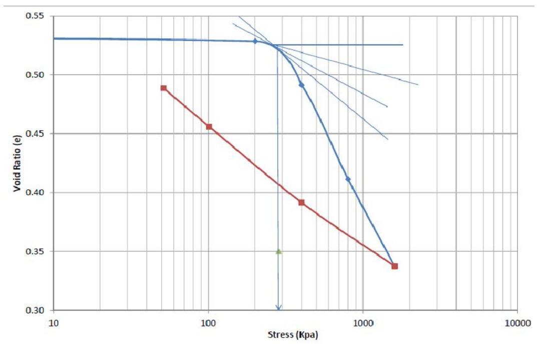


Fig. 8 Constant Volume Test Results

Fig. 9 shows a comparison between the three methods, which use to determine the swelling pressure.

The results indicates the there is a difference between the results of the three tests, the loaded swell test gives the maximum swelling pressure, where the constant volume test give the minimum one.

This comparison shows that the loaded swell test has an advantage in the prediction of the vertical strain versus the applied net vertical stress.

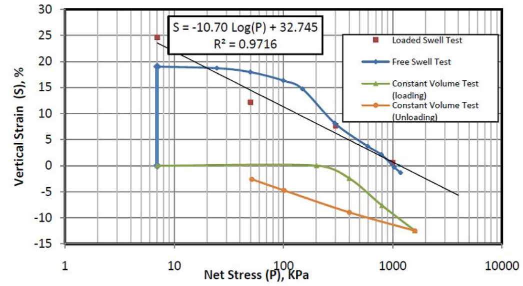
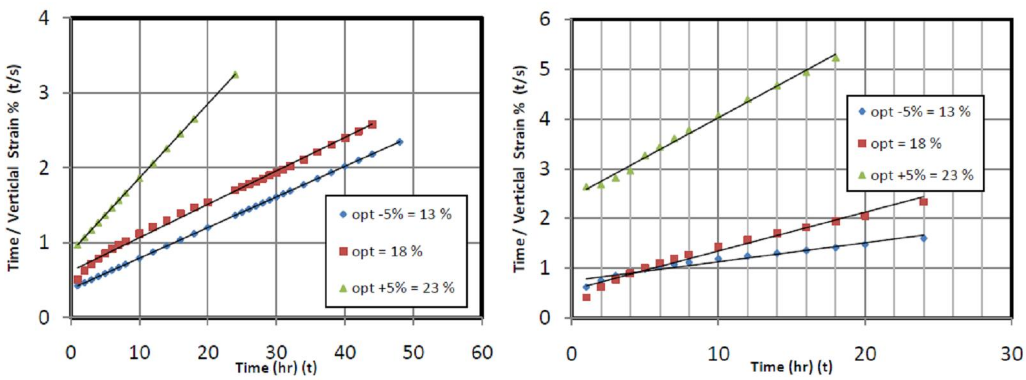
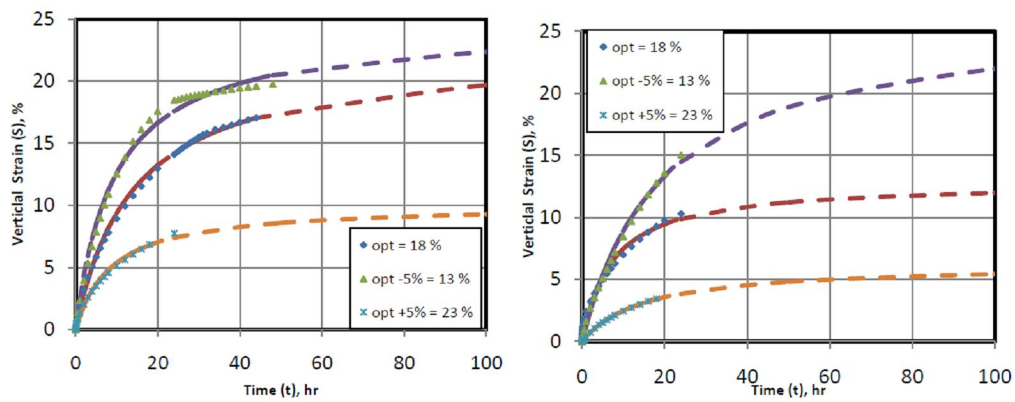


Fig. 9 Results of Free Swelling Test, Loaded Swell Test and Constant Volume Test



(a) (b)

Fig. 10 Time/Vertical Swell Versus Time from Swelling Potential Test. (a) D=50.8 mm – H=19 mm, (b) D=63.5 mm – H=25 mm



(a) (b)

Fig. 11 Time Versus Vertical Swell from Swelling Potential Test. (a) D=50.8 mm – H=19 mm, (b) D=63.5 mm – H=25 mm

Swelling potential test

The swelling test is performed on a soil sample at Maximum dry density at the optimum moisture content and at ± 5% to evaluate the effect of the initial moisture content of the value of axial strain. To predict the maximum axial strain, the same procedure of analysis the results of the loaded swell test is performed. Fig.10-a and Fig.10-b show the relation between time (t) and time divided by axial strain (t/s) for the two sizes of the tested samples, Also Fig.11-a and Fig.11-b show the relation between time (t) and axial strain (s) and predicted relations.

The maximum swelling potential of soil at variable moisture content is summarized at table 2, the test results show that the initial moister content and the samples dimensions have an effect on the swelling potential results. For the small sample size, decreasing the optimum moisture content by 5% increases the swelling potential by 9.12%. Increasing the water by 5% decreases the swelling potential by 55%.

For the large sample size, decreasing the optimum moisture content by 5% increases the swelling potential by 104.6%. Increasing the water by 5% decreases the swelling potential by 51.3%.

Table 2. Swelling Potential with Respect to Initial Water Content

Soil initial water content	Swelling Potential	
	Size 1	Size 2
At optimum W.C	22.42 %	12.83 %
At Dry of optimum = W.C-5%	24.48 %	26.25 %
At Wet of optimum = W.C+5%	10.10%	6.25

Suction test results

The filter paper indirect method is used with eight points at degree of saturation (89.94%, 80.44%, 74.99%, 68.67%, 59.75%, 52.15%, 44.23% and 36.09%). The fitting equation of Fredlund and Xing 1994 (Eqn 1) is used for soil water characteristic curve (SWCC). The values of fitting parameters (a, m and n) are 883.5, 0.6183 and 1.266 as shown in Fig.12, the air entry value is 100kPa, the residual degree of saturation is 23.7%, the residual suction is 46200 kPa and the residual water content is 8.3%.

$$U_m = a * \left[e^{\left(S_{sat}/S_r\right)^{1/m}} - e \right]^{\frac{1}{n}} \qquad (1)$$

Where :

S_r = Degree of saturation at certin matic suction

S_{Sat} = Degree of saturation at Saturation = 100%

U_m = Matric Suction (kPa)

$a - m - n$ = Equation fitting parameters

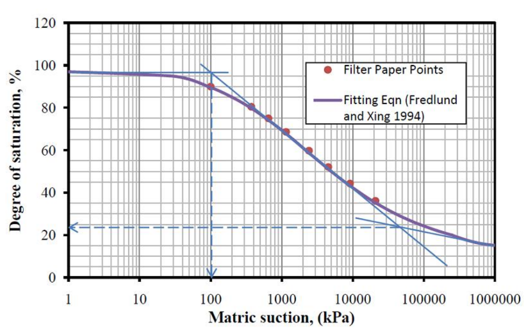


Fig. 12 Soil Water Characteristic Curve of Soil

Shear test results

The shear tests are performed on samples six different degree of saturation of (100%, 63.28%, 57.14%, 49.48%, 42.4% and at 36.57%), At each degree of saturation, three tests are performed at vertical stress of (100 kPa, 200 kPa and 400 kPa), Linear fitting of each degree of saturation to get the value of undrained shear strength is performed. The tests data are shown if Fig.13.

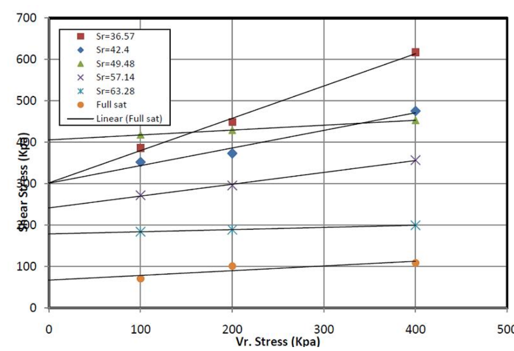


Fig. 13 Soil Shear Strength at Different Values of Matric Suction

(Garven and Vanapalli 2006) has summarized models to predict the shear strength of the unsaturated soil. All these models have a function of two terms, the first term is the shear strength at saturation while the second term (τ_{su}). is the shear strength contributed due to suction as shown in Eqn2.

$$\tau = [C + (\sigma_n - U_a) * \tan\phi] + \tau_{su} \qquad (2)$$

The term of (τ_{su}) is always a function of three parts matric suction value, the saturated internal angle of friction and (X) as shown in Eqn3.

$$\tau_{su} = X * (U_a - U_w) * \tan\phi \qquad (3)$$

The term (X) is related to (SWCC) shape such as air entry value and residual degree of saturation. It is varied in each model, Table 3 summarized these models to predict the shear strength of unsaturated soils.

Table 3. Different Models of Prediction of the Shear Strength of Unsaturated Soils

	No.	Equation
(Vanapalli et al. 1996)	Eqn 4	$\tau = [C' + (\sigma_n - U_a) * \tan\phi'] + \Theta^K * (U_a - U_w) * \tan\phi'$ C' = Effective cohession ϕ' = Angle of friction resistance $(\sigma_n - U_a)$ = Normal stress $(U_a - U_w)$ = Matric suction Θ = Normalized water content K = Fitting parameter
(Vanapalli et al., 1996)	Eqn 5	$\tau = [C' + (\sigma_n - U_a) * \tan\phi'] + \frac{\theta_w - \theta_r}{\theta_S - \theta_r} * (U_a - U_w) * \tan\phi'$ θ_w = Volumetric water content θ_r = Residual volumetric water content θ_S = Saturated volumetric water content
(Öberg and Sällfors 1997)	Eqn 6	$\tau = [C' + (\sigma_n - U_a) * \tan\phi'] + S * (U_a - U_w) * \tan\phi'$
(Chenggang et al. 1998)	Eqn 7	$\tau = [C' + (\sigma_n - U_a) * \tan\phi'] + \left[\frac{\log(U_a - U_w)_r - \log(U_a - U_w)}{\log(U_a - U_w)_r - \log(U_a - U_w)_b}\right] * (U_a - U_w) * \tan\phi'$ $(U_a - U_w)_r$ = Residual Matric suction $(U_a - U_w)_b$ = Air Entry Value

Figures (14, 15, 16 and 17) illustrate a comparison between the four models is performed at variable vertical stress of values 0,100 kPa, 200 kPa and 400 kPa).

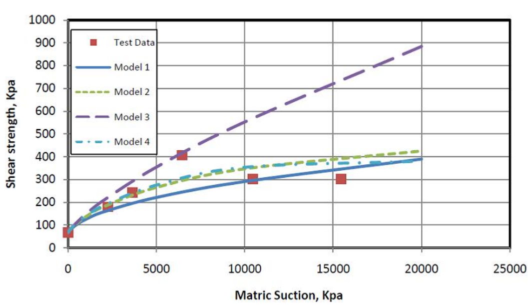


Fig. 14 Soil Shear Strength of Unsaturated Soil Versus Soil Matric Suction (Net Normal Stress=0 kPa)

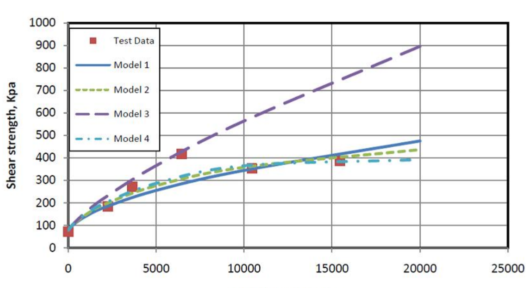


Fig. 15 Soil Shear Strength of Unsaturated Soil Versus Soil Matric Suction (Net Normal Stress = 100 kPa)

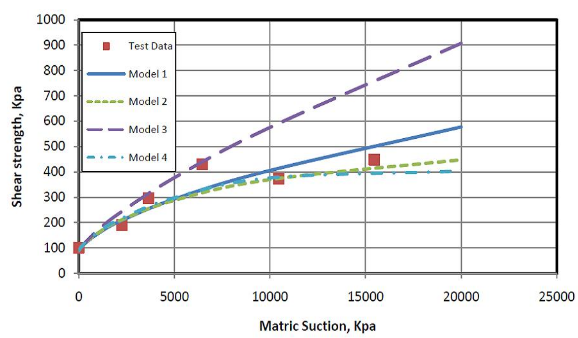


Fig. 16 Soil Shear Strength of Unsaturated Soil Versus Soil Matric Suction (Net Normal Stress = 200 kPa)

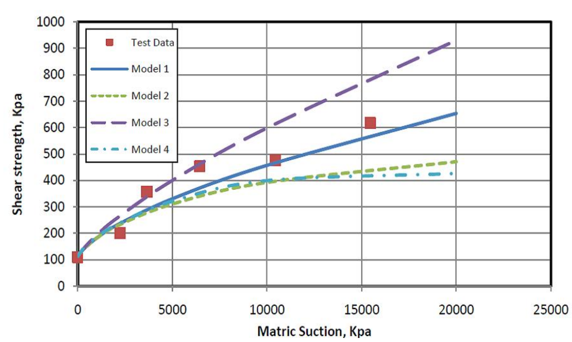


Fig. 17 Soil Shear Strength of Unsaturated Soil Versus Soil Matric Suction (Net Normal Stress = 400 kPa)

The comparison of the different models and the test data shows that, at low values of normal stress till 100 kPa, models 1, 2 and 4 give a responsible results of prediction of soil shear parameters, while model 3 gives overestimated values of shear strength specially at high matric suction value. Where at high values of normal stress (200 kPa to 400 kPa), the model 2 and model 4 gives underestimated values of soil shear strength especially at high values of matric suction. Model 3 gives suitable estimated values of soil shear strength at low suction values, although it gives overestimated values at high matric suction values.

Conclusions

1. For tested soil, the results of the different procedures in odometer test have an effect on the value of swelling pressure, swelling pressure obtained from LS test is 1150 kPa. The swelling pressure obtained from FS test is 1000 kPa. The corrected swelling pressure obtained from CV test is 318 kPa.

2. The test results show that the initial moister content and the samples dimensions have an effect on the swelling potential results. For the small sample size, decreasing the optimum moisture content by 5% increases the swelling potential by 9.12%. Increasing the water by 5% decreases the swelling potential by 55%. For the large sample size, decreasing the optimum moisture content by 5% increases the swelling potential by 104.6%. Increasing the water by 5% decreases the swelling potential by 51.3%.

3. The comparison of the different models and the test data shows that, at low values of normal stress till 100 kPa. The three models of (Vanapalli et al. 1996), and (Chenggang et al. 1998) give a responsible results of prediction of soil shear parameters, where (Öberg, A L and Sällfors, G, 1997) model gives over estimatied values specially at high matric suction value. Where at high values of normal stress (200 kPa to 400 kPa), Vanapalli et al., (1996) (Eqn 5) and Chenggang et al., (1998) models give underestimated values of soil shear strength especially at high values of matric suction. Öberg, A L and Sällfors, G, (1997) model gives suitable estimated values of soil shear strength at low suction values, although it gives overestimated values at high matric suction values.

References

1. ASTM:D1557 – 09. (2011). "Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3(2,700 kN-m/m3))." *Annual Book of ASTM Standards*, 4(C), 1–14.
2. ASTM:D2487 – 06. (2006). "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)." *ASTM Standard Guide*, D5521-05(June 2006), 1–5.
3. ASTM:D422 – 63. (2007). "ASTM D422: Standard Test Method for Particle-Size Analysis of Soils." *ASTM Standard Guide*, i (Reapproved 2007), 1–8.
4. ASTM:D4318 – 05. (2005). "Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." *Report*, 04(March 2010), 1–14.
5. ASTM:D5298 – 03. (2003). "Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper 1." 11(November 1994), 4–11.
6. ASTM:D54-06. (2010). "This standard is for EDUCATIONAL USE ONLY. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer 1 This standard is for EDUCATIONAL USE ONLY." *Annual Book of ASTM Standards*, i (C), 1–7.
7. ASTM:DD2435 – 04. (2010). "Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using This standard is for EDUCATIONAL USE ONLY." *Annual Book of ASTM Standards*, i, 1–10.
8. ASTM D4546 – 08. (1996). "Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive." *Astm International*, 1–7.
9. Basma, A. A., Al-Homoud, A. S., and Husein, A. (1995). "Laboratory assessment of swelling pressure of expansive soils." *Applied Clay Science*, Elsevier, 9(5), 355–368.
10. Chenggang, B., Biwei, G., and Liangtong, Z. (1998). "Properties of unsaturated soils and slope stability of expansive soils." *Proc. the Second International Conference on Unsaturated Soils*.
11. Garven, E. A., and Vanapalli, S. K. (2006). "Evaluation of empirical procedures for predicting the shear strength of unsaturated soils." *Unsaturated Soils 2006*, 2570–2592.
12. Gilchrist, H. G. (1963). "A study of volume change of a highly plastic clay." Saskatchewan.
13. Justo, J. L. et al. (1984). "The influence of stress-path in the collapse-swelling of soils at the laboratory." *Fifth International Conference on Expansive Soils 1984: Preprints of Papers*, Institution of Engineers, Australia, 67.
14. Khaddaj, S. et al. (1992). "Experimental study of the swelling behavior of heavily over consolidated Flandres clay." *Proc. 7th Int. Conf. Expansive Soils (DallasTexas)*, 239–244.
15. Nagaraj, H., Munnas, M., and Sridharan, A. (2010). "Swelling behavior of expansive soils." *International Journal of Geotechnical*

Engineering, Taylor & Francis, 4(1), 99–110.
16. Noble, C. A. (1966). "Swelling measurements and prediction of heave for a lacustrine clay." *Canadian Geotechnical Journal*, NRC Research Press, 3(1), 32–41.
17. Öberg, A. L., and Sällfors, G. (1997). "Determination of shear strength parameters of unsaturated silts and sands based on the water retention curve." *Geotechnical Testing Journal*, ASTM International, 20(1), 40–48.
18. Sridharan, A., Rao, A. S., and Sivapullaiah, P. V. (1986). "Swelling pressure of clays." *Geotechnical Testing Journal*, ASTM International, 9(1), 24–33.
19. Vanapalli, S. K., Fredlund, D. G., Pufahl, D. E., and Clifton, A. W. (1996). "Model for the prediction of shear strength with respect to soil suction." *Canadian Geotechnical Journal*, NRC Research Press, 33(3), 379–392.
20. Vanapalli, S., and Lu, L. (2012). "A state-of-the art review of 1-D heave prediction methods for expansive soils." *International Journal of Geotechnical Engineering*, Taylor & Francis, 6(1), 15–41.

8/13/2018