Effect of Initial Water Content on the Properties of Compacted Expansive Unsaturated Soil

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ABSTRACT

Unsaturated soil can raise many geotechnical problems upon wetting and drying resulting in swelling upon wetting and collapsing (shrinkage) in drying and changing in the soil shear strength. The classical principles of saturated soil are often not suitable in explaining these phenomena. In this study, expansive soil (bentonite and sand) were tested in different water contents and dry unit weight chosen from the compaction curve to examine the effect of water content change on soil properties (swelling pressure, expansion index, shear strength (soil cohesion) and soil suction by the filter paper method). The physical properties of these soils were studied by conducting series of tests in laboratory. Fitting methods were applied to obtain the whole curve of the SWRC measured by the filter paper method with the aid of the (Soil Vision) program. The study reveals that the initial soil conditions (water content and dry unit weight) affect the soil cohesion, soil suction and soil swelling, where all these parameters marginally decrease with the increase in soil water content especially on the wet side of optimum.

Key words: expansive soil, swelling, filter paper, SWRC, swelling pressure.

تاثير المحتوى المائي الابتدائي على خصائص تربه عراقية انتفاخية محدوله غير مشبعة

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الخلاصة

التربه غير المشبعة يمكن ان تثير العديد من المشاكل تحت تاثير الترطيب و التجفيف مسببة الانتفاخ تحت تاثير الترطيب و الانكماش تحت تاثير التجفيف وتغيير في مقاومة القص للتربه. المبادئ الاساية للترب المشبعة هي عادة غير مناسبة في تفسير مثل هذه الظواهر. في هذه الدراسة, التربة الانتفاخية من (البنتونايت و الرمل) تمت دراستها في محتوى مائي و كثافة اوليه مختلفة من منحني الرص المختبري لدراسة تاثير تغير المحتوى المائي على خصائص التربة (الضغط الانتفاخي, معدل الانتفاخ,مقاومة القص (تماسكية التربة) و اجهاد المص للتربة بطريقة ورق الترشيح). الخصائص الفيزيائية للتربة تمت دراستها بالاستعانة بالعديد من الفحوص المختبريه. تم استخدام المعادلات التكميلية لايجاد المنحني الكامل للعلاقة بين المحتوى المائي و اجهاد المص في التربه بالاستعانة ببرنامج (Soil Vision). بينت الدراسة بان ظروف التربة الابتدائية (المحتوى المائي و الكثافة الاوليه) تؤثر على

تماسكية التربة و انتفاخيتها و اجهاد المص فيها حيث ان هذه الخصائص الثلاثة تقل بشكل كبير بزيادة المحتوى المائي الابتدائي خاصة على الجهة الرطبة من منحني الرص المختبري.

الكلمات الرئيسيه : تربة انتفاخية, الانتفاخ, ورق ترشيح, الضغط الانتفاخي

1. INTRODUCTION

The soil forming at shallow depths in the arid and semi-aired regions and the compacted soil used in highways, earth dams, embankments and airport runways are in unsaturated conditions. Whenever water interacted to such soils, volume changes could happen. Such a reaction between the soil and the water may cause collapse or swelling to soils depending on soil conditions. Usually these volume changes are small in magnitude. However, for particular types of soils (expansive soils), these volume changes are of considerable order. Such soils either suck in or lose a large amount of water during hydration or dehydration process. For shallow foundations, soil swelling and soil shrinkage may cause considerable problems, because the wetting may cause a reduction in the soil shear strength and an increase in the soil hydraulic conductivity and shrinkage may cause cracks in different parts of the structure, **Abed, 2008**.

Many financial losses are reported all over the world due to the lack of the correct understanding of the behavior of expansive soil. To close the knowledge gap in this field, serious research on this topic started in the middle of 1960s. Several conferences have been held since then and produced the so called " the unsaturated soil mechanics" as an independent science with extended rules as compared to classical soil mechanics. Today studying the expansive soil cannot be separated from the unsaturated soil mechanics, **Smith, 2003**.In Iraq, expansive soils spread in large area in the north, middle and south of Iraq.

2. UNSATURATED SOILS

Unsaturated soils may be defined as the soil which has four phases: soil, water, air and air-water interface or the "contractile skin". The contractile skin is considered as a fourth phase since it has definite bounding and different properties from the contiguous materials". The presence of small air in soil renders the soil to be unsaturated, **Fredlund, and Rahardjo, 1993**. The soil below the water table is fully saturated and the pore water pressure has a positive value. The ground water table is considered as the line at which the pore water pressure will be equal to zero (relative to atmospheric). Above the water table the soil will be in an unsaturated state where the pore water pressure has a negative value.

2.1 Soil Suction

Porous materials like soil have the ability to absorb and retain water. This property has an engineering definition which is "suction". Suction may be defined as the free energy of soil water. Suction in soil consists of two components matric (matrix) suction and osmotic suction, **Fredlund, and Rahardjo, 1993**. In unsaturated soil mechanics, the matric suction is notably defined as the difference between the pore air and pore water pressure (u_a-u_w). The summation of these components gives the total suction. Matric suction generates from capillarity, texture, and surface adsorption forces, while the osmotic suction comes from the effect of the dissolved salts in the soil water. According to, ,**Fredlund, 1969,** the osmotic suction is always neglected. This relation can be formed in an equation as follows:

$$h_t = h_m + h_\pi \quad (1)$$

where h_t = total suction (kPa),
h_m = matric suction (kPa),
h_π = osmotic suction (kPa).

The magnitude of soil suction ranges from a lower limit equals to zero when the pore water pressure equals to zero and theoretically no dissolved salts in soil water and an upper limit which equals to 1,000,000 kPa. This case occurs when there is zero water content (dry soil).

2.2 The Soil Water Characteristic Curve (SWCC)

The soil water characteristic curve may be defined as the graphical representation of the mathematical relation between the volumetric water content (the ratio of volume of water to the total volume of soil), gravimetric water (the ratio of the mass of water to the mass of solids) or the degree of saturation (S) and the matric suction, **Fredlund, et al., 2001**. In case of increasing the suction (drying) for initially saturated, slurry or compacted, soils the resulted curve is called the (SWCC), while in case of initial unsaturated state soils, the curve will identify as the soil water retention curve (SWRC) which has the same definition, ,**Al-Badran, 2011**. The SWCC may be measured by different methods: a) experimental methods (i. e. the Fredlund and Xing and the van Genuchten equations used in this paper), b) estimated from the pore size distribution (PSD), c) experimental methods (i. e. the filter paper method used in this paper).

2.3 The Filter Paper Method

The initial water content of the compacted soil appears to have direct relationship to the soil matric suction, while the osmotic suction does not seem to be sensitive towards the changes in the soil water content. It is one of the indirect methods for measuring matric and osmotic suction, the filter paper will absorb the moisture from the soil until reaching the equilibrium state (by either liquid or vapor moisture exchange) where the water content will be equal in the filter paper and the soil, **Bulut, et al., 2001**.

The liquid exchange will happen when the filter paper is in contact with the soil and in this case the matric suction will be measured, while the vapor exchange will happen when the filter paper is not in contact with the soil from which the total suction will be measured. This method however will need a calibration for suction versus water content relation in filter paper. The main advantages of this method are the low cost as compared to the other methods and the capability to measure wide range of suction (full range of suction in case of contact filter paper). The accuracy of the filter paper technique depends on the accuracy of the suction versus water content calibration curve. The filter paper used should be the ash free filter paper like the most commonly used ones Whatman No.42 and Schleicher and Schuell No.589 WH.

2.4 Expansive Unsaturated Soil

Expansive soil is that kind of problematic soil which shows a significant amount of volume changes upon wetting and drying. The amount of swell generally increases with the increase in soil's plasticity index, **Ameta, et al., 2008**.

Expansive soil problems to foundations are heaving, cracking and break up to light structures like pavements. The effect of heave is to reduce the soil shear strength and thus reducing the stability of the structure and causing total and differential settlement, **Sridharan, et al., 1987**. It is true to consider the expansive soil as soft soil under wet condition. Swelling soil can virtually control the behavior of any soil type if the amount of clay is more than 5% by weight, **Rogers, et al., 1993**. The clay minerals containing montmorillonite show significant swelling upon wetting as compared to the clay soil containing other clay minerals like kaolinite or illite which shows significant decrease in volume upon drying but limited increase in volume caused by wetting, **Chen, 1975**.

2.5 Mechanism of Swell

Mitchell, 1993. showed that soil swelling happens due to several factors:

1-Capillary Imbibition: The surface tension caused by air in the unsaturated soil and the soil suction caused water adsorption to the soil system.

2-Osmotic Imbibition: The double layer acts as semi permeable membrane with difference in the ion's concentration inside and outside of it causing the flow of water and increase in the soil volume.

3- Hydration of Exchangeable Cations: as described previously the cations attracted to the negatively charged soil surface causing an increase in the volume of the double layer. Then these cations will be hydrated causing an increase in the ion's volume and as a result an increase in the soil volume.

4-Van Der Waals forces: these forces are secondary in-directional forces and less strong than the hydrogen bonding and they connect the montmorillonite sheets, when adsorption of water happens a repulsion between these forces will happen leading to an increase in the volume of soil.

The objective of the present work is to model the behavior of the expansive soil in the framework of unsaturated soil mechanics. This work was used to predict the volume changes associated with the changes in soil suction.

3. EXPERIMENTAL WORKS AND MATERIAL USED

In this study, the aim was to study the effect of initial water content on the properties of compacted expansive soil. Different mixtures of bentonite (brought from Al-Falouja city west of Baghdad) with sand (from Ali Al-Gharbi city south of Baghdad) were tested till getting the mixture of 80% of bentonite to 20% of sand (B-S) by dry weight depending on the required plasticity indices. The physical and chemical properties of these soils are presented in **Table 1.** and **Table 2**. respectively. **Fig. 1** shows the grain size analysis of the soils by the wet sieving method according to ASTM D 1140-00 for bentonite and the (B-S) soil and the dry sieving according to ASTM D 422-02 was used to the sand soil. **Fig. 2** shows the compaction curve of the soils.

Four points were chosen from the compaction curve, **Fig. 2** (two from the dry side, the optimum moisture content and one from the wet side). **Table 3,** shows the water content and the dry unit weight used to prepare the samples. The oven dried soil was left to cool down at room temperature and then mixed with the required water to get the targeted water content. The samples were left to cure in two plastic bags for one day as followed by ,**Agus, et al., 2010,** and then prepared by the moist tamping system recommended by ,**Chao, 2007.**

3.1 Measurements of Soil Suction

The test was done according to ,**ASTM D, 5298-03**. The soil samples were remolded in two odometer rings 75 mm in diameter and 19 mm in height, three filter papers (Whatman 42) were sandwiched between these two soil samples and two filter paper were separated from the soil sample by a PVC ring of 2.5 cm in thickness as followed by ,**Fattah, et al., 2013. a and b.** This group of soil samples and filter papers were placed in glass cylinder where the samples filled about two third of the cylinder space as recommended by ,**Bulut, et al., 2001.** to reduce the equilibrium time. The samples were left to get the equilibrium condition for about ten days ,**Sridharan et al., 1987**. Then the wet filter papers were weighed to the nearest 0.0001gm quickly as possible, the filter papers were placed in a jarred tins and inserted in the oven of 105 ^{0}C for six hours and weighed again as recommended by ,**Chao, 2007.**

3.2 Unconfined Compression Test

The unconfined compression test was done according to the ,**ASTM D, 2166-00**. The soil samples were remolded in the unconfined compression tube 3.8 cm in diameter and 15 cm in length, the extracted samples were cut to produce a soil sample of only 7.6 cm length which will be tested in the triaxial machine at a rate of 1.5 mm/minute. This test is basically used to quickly find the unconfined compression strength (q_u) of the soil by which the shear strength of the soils can be computed as:

$$c = q_u/2 \tag{2}$$

where c is the soil cohesion.

3.3 The Swelling Test

The test was done according to ,**ASTM D, 4829-03**. In these tests, the oven dried soil passing 2mm sieve was mixed with the required amount of water and were remolded at the oedometer ring (75 mm in diameter and 19 mm in height) but the sample was prepared by a height equal to 14 mm to insure that the specimen will be laterally confined ,**Al-Omari, et al., 2010**. A load of about 7 kPa was applied as seating pressure, left for ten minutes then an initial reading was recorded. The soil sample was submerged with distilled water for 24 hours then the final reading was recorded. To measure the swelling pressure, weights will be added in increments to the soil sample to get the dial gage reading zero again.

4. RESULTS OF TESTS

4.1 Results of Unconfined Compression Test

Fig. 3 shows the relation between the unconfined compressive strength and the initial water content of the B-S soil. The figure shows that the unconfined compressive strength (q_u) decreased with the increase in the soil water content from 479 kPa to 320 kPa when the water content increased from 23% to 30.5%. Suction contributes to increase the soil strength which is reflected as the shear strength contribution due to suction (i.e., $Ø^b$), the cohesion in unsaturated soil is combined of two components; the effective cohesion and the cohesion due to suction, Eq. (3), **Fredlund, and Rahardjo, 1993.**

$$c = \acute{c} + (u_a - u_w) \tan \varnothing^b \qquad (3)$$

However, the ($\varnothing^b$) decreases with the increase in soil suction but in the case of undrained loading condition, the increase in the soil shear strength due to applying pressure is greater than the decrease in shear strength due to decreasing the matric suction, where the specimens tested with lower water contents have lower shear strength in drained loading conditions, these specimens show higher strength in the undrained condition, **Vanapalli, et al., 1999**. The initial matric suction of specimen compacted at dry of optimum and optimum water content is higher compared to specimen compacted wet of optimum. Due to this reason, specimen at dry side of optimum and at optimum show more resistance to deformation than specimen wet of optimum, where the soil strength and stiffness increases with the increase in soil suction as stated by ,**Nishimura, and Vanapalli, 2004**.

4.2 Results of Swelling Tests

Fig. 4 shows the relation between the swelling pressure and the initial water content, while **Fig. 5** shows the relation between the expansion index and the initial water content of soil suction. The figures show that the swelling pressure and the expansion index decrease with the increase in the soil initial water content and that could be attributed to the soil structure which is more dispersed at higher water contents and the natural desire of the soil to imbibe water to satisfy the double layer. This desire decreases with increasing water content, **Sudjianto, et al., 2009**. The results show that compacting the expansive soil on the wet side of optimum is capable of removing major component of swelling pressure from 275 to 162.5 kPa when the moisture changes by 7.5 %. According to ,**Ameta, et al., 2008**. the swelling pressure increases with the increase in the dry unit weight and decreases with the increase in the initial molding water content, however the effect of the initial molding water content is more effective than the dry unit weight in reducing or increasing the swelling pressure especially on the dry side of optimum.

,Zumrawi, 2013, showed that there is an inverse linear relationship of the swelling percent and the swelling pressure with the initial water content with constant dry unit weight, while a linear relationship may be obtained between the swelling percent and swelling pressure with the initial dry unit weight if the initial water content is constant. The same conclusion was obtained in this work but the relation is not linear since both the initial water content and the initial dry unit weight were not constant.

4.3 Results of the Filter Paper Test

Fig. 6 shows the relation between the initial soil water content with the total and matric suction, while **Fig. 7** shows the relation between the filter paper water content and the total and matric suction. The figures show a linear relationship between the suction (total and matric) with filter paper water content for both soils showing a linear increase in suction with the decrease in the filter paper water content. The results also show that the suction (total and matric) decreases with the increase in the soil water content but this relation does not have a linear trend. The rate of increasing the water content is not equal to the rate of decreasing the soil suction. The inverse relationship between the water content or the soil degree of saturation with suction could be explained by the fundamental meniscus theory as follows, when the water content increases, the radius (Rs) of the meniscus will also increase. When (Rs) increases, the pressure difference between the pore air pressures and the pore water pressure (matric suction) will decrease as illustrated in Eq. (4), ,**Ravichandran, and Krishnapillai, 2011**.

$$u_a - u_w = 2T_s/R_s \tag{4}$$

where: T_s is the surface tension.

Fig. 8 shows the SWRC as measured by the Fredlund and Xing equation with the aid of Soil Vision program after inserting the required soil properties (specific gravity, dry unit weight, grin size analysis and at least three points of water content with corresponding suction measured by the filter paper method). **Fig. 9** shows the SWRC estimated by van Genuchten equation.

4.4 Relations between the Soil Suction and the Unconfined Compressive Strength

Fig. 10 shows the relation between the soil suction with the unconfined compressive strength of the soil where a nonlinear increase in the unconfined compressive strength with the both suction components due to the effect of suction to increase the soil resistance to deformation and increasing the soil strength.

By increasing the soil suction the soil wetness decreased and the contact between the soil particles decreased causing reducing in the soil cohesion.

5. CONCLUSIONS

Based on the experimental results of the experimental work, the following conclusions may be obtained:

1- The soil unconfined compressive strength increased with the increase in soil suction and with decrease the soil water content, where the soil cohesion decreased from 248.5 to 134 kPa when the initial water content increased by 7.5% due to the effect of matric suction which leads to increase the soil cohesion component of soil shear strength.

2- The swelling potential of the soil increased with increase of soil suction and with the decrease in the soil initial water content and this increase is greater for samples prepared at the dry of optimum water contents. The swelling pressure decreased from 287.5 to 162.5 kPa and the expansion index decreased from 276 to 160.8 when the moisture changes by 7.5%. The natural desire of the soil to imbibe water to satisfy the double layer decreases with increasing water content.

3- Both total and matric suction decreased with the increase in the initial soil water content and a linear relationship was obtained between the two suction components and the filter paper water content.

REFERENCES

- Abed, A., 2008. *Numerical Modeling of Expansive Soil Behavior,* Ph.D. Thesis, University of Stuttgart.
- Agus, S. S., Schanz, T., Fredlund, D. G., 2010. *Measurements of Suction versus Water Content for Bentonite – Sand Mixtures,* Geotechnical testing Journal Vol. 126, No.2, pp. 179-190.
- Al-Badran, Y. M. H., 2011. *Volumetric Yielding Behavior of Unsaturated Fine-Grained Soils,* Ph.D. Thesis, Faculty of Civil and Environmental Engineering, University of Bochum, Germany.
- Al-Omari, R. R., Ibrahim, S. F. and Al-Bayati, I. K., 2010. *Effect of Potassium Chloride on Cyclic Behavior of Expansive Clays*, International Journal of Geotechnical Engineering, Vol. 4, No.2, pp. 231-239.
- Ameta, N. K., Purohit, D. G. M. and Wayal, A.S., 2008. *Characteristics, Problems and Remedies of Expansive Soils of Rajasthan, India,* Electronic Journal of Geotechnical Engineering, EJGE, Vol.13.
- ASTM D 1140-00, 2000. Standard Test Methods *for Amount of Material in Soils Finer Than the No. 200 sieve, Reprinted from the Annual Book of ASTM Standards.* Copyright ASTM, Vol.4, No.8.
- ASTM D 2166-00 , 2000. *Standard Test Method for Unconfined Compressive Strength of Cohesive Soil,* Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.
- ASTM D 2487-00, 2000. *Standard Practice for Classification of Soils for Engineering Purposes* (Unified Soil Classification System*), Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.*
- ASTM D 422-02, 2012. *Standard Test Method for Particle-Size Analysis of Soils,* Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.

- ASTM D 4254-00, 2000. *Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density,* Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.
- ASTM D 4318-00, 2000, *Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils,* Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.
- ASTM D 4829-03, *2003, Standard Test Method for Expansion Index of Soils,* Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.
- ASTM D 5298-03, 2003. *Standard Test Method for Measurements of Soil Potential (Suction) by Filter Paper,* Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.
- ASTM D 698-12, 2012. *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (600KN-m/m^3),* reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.
- ASTM D 854-00, *2000. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer,* Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.
- Budhu, M., 2011, *Soil Mechanics and Foundations*, University of Arizona, USA.
- Bulut, R., Lytton, L. and Wray, W. K., 2001, *Soil Suction Measurements by Filter Paper*, Geotechnical Special Publication, No. 115., Proceedings of Geo-Institute Shallow Foundation and Soil Properties Committee Sessions at the ASC,E 2001,Civil Engineering Conference, Texas, pp. 243-261.
- Chao, K. H., 2007, *Design Principles for Foundations on Expansive Soil,* Ph.D. thesis, Colorado State University.
- Chen, F.H., 1975, *Foundations on Expansive Soils,* Elsevier, Amsterdam.
- Fattah, M. Y., Ahmed, M. D. and Mohammed, H.A., 2013a, *Behavior of Partially Saturated Cohesive Soil under Strip Footing,* Journal of Engineering, Vol. 19, No.3, pp. 298-311.

- Fattah, M. Y., Yahya, A. Y., Al-Hadidi, M. Th. and Ahmed, B. A., 2013b, *Effect of Salts Content on Total and Matric Suction of Unsaturated Soils,* European Scientific Journal ESJ, Vol.9, No.9.
- Fredlund, D.G., 1969, *Consolidometer Test Procedural Factors Affecting Swell Properties, 2nd International Conference on Expansive Clay Soils,* Texas, U.S.A., pp. 435-456.
- Fredlund, D. G., and Rahardjo, H., 1993, *Soil Mechanic for Unsaturated Soils,* John Wiley & Sons Inc. New York, USA.
- Fredlund, D. G., Rahardjo, H., Leong, E. C., and Ng, C. W. W., 2001, *Suggestions and Recommendations for the Interpretation of Soil–Water Characteristic Curves,* Proc. 14th Southeast Asian Geotechnical Conference, Hong Kong, pp. 503 – 508.
- Mitchell, J. K., 1993, *Fundamentals of Soil Behavior,* 3rd edition, John Wiley and Sons, New York, USA.
- Nishimura T. and Vanapalli S. K., 2004, *Shear Strength Behavior of an Unsaturated Soil in Low and High Suction Range under Constant Volume Conditions, 57th Canadian Geotechnical Conference, Quebec, section 6E, pp.17-24.*
- Ravichandran, N. and Krishnapillai, S. H., 2011, *A Flexible Model for Moisture-Suction Relationship for Unsaturated Soils and its Application,* International Journal of Geosciences IJG, Vol.2, No.3, pp. 204-213.
- Rogers, J. D., Olshansky, R. and Rogers R. B., 1993, *Damage to Foundations from Expansive Soils*, Claims People, Vol. 3, No.4, pp.1-4.
- Smith, P. G. C., 2003.,*Numerical Analysis of Infiltration into Partially Saturated Soil Slopes,* Ph.D. Thesis, Department of Civil and Environmental Engineering, University of London.
- Sridharan, A., Rao, A.S. and Sivapullaiah, P.V., 1987, *Swelling Pressure of Clays, Geotechnical Testing Journal, American Society for Testing and Materials,* Vol. 9, No.1, pp. 24-33.
- Sudjianto, A. T. Suryolelono, K.B., Rifa, A. and Mochtars, I. B., 2009,*Behavior of Expansive Clay of Ngawi Region (East Javal) Under Water Content Variation,* Civil Engineering Dimension, Vol.11, No. 2, pp. 100-105.

- Vanapalli, S. K., Fredlund, D. G. and Pufahl, D. E., 1999. *The Relationship between the Soil Water Characteristic Curve and the As-Compacted Water Content Versus Soil Suction for a Clay Till*, Proceedings of the 11th Pan American Conference on Soil Mechanics and Geotechnical Engineering, pp.991-998.
- Zumrawi, M. E., 2013, *Swelling Potential of Compacted Expansive Soils*, International Journal of Engineering Research and Technology (ISERT), Vol. 2, No. 3, pp. 1-6.

Table 1. The physical properties of soils prepared.

Physical Properties	B-S	Specification
Specific gravity (Gs)	2.83	ASTM D 854
Liquid Limit (L.L)	104	ASTM D 4318
Plastic Limit (P.L)	41	ASTM D 4318
Plasticity Index (P.I)	63	ASTM D 4318
% clay	55	ASTM D 1140, D 422-02
% silt	23	
% sand	22	
Activity (A) %	1.15	Budhu, 2011
Optimum Moisture Content % (O.M.C)	28	ASTM D 698-12
Maximum Dry Unit Weight $(\gamma_{dry})_{max}$ (kN/m^3)	14.976	ASTM D 698-12
Minimum Dry Unit Weight (kN/m^3)	---	ASTM D 4254
C_c, C_u for Sand	---	ASTM D 4254
e (void ratio)	0.89	----
Soil Symbols according to USCS	CH	ASTM D 2487

Table 2. Chemical properties of soils used.

Chemical Properties	Bentonite	Sand
SO_3	2.27	0.05
Organic	0.59	Nil
Gypsum	4.7	0.1075
TSS	6.1	0.15
SiO_2	51.92	55.55
CaO	1.96	11.25
Na_2O	0.13	1.73
MgO	0.27	3.9
Cl	0.17	0.06
pH	9.14	8.65

Table 3. Water content and dry unit weight of soil sample.

Soil Type	Water Content	γ_{dry} (kN/m^3)
B-S mixture	23%	14.66
B-S mixture	25.5%	14.90
B-S mixture	28%	14.976
B-S mixture	30.5%	14.90

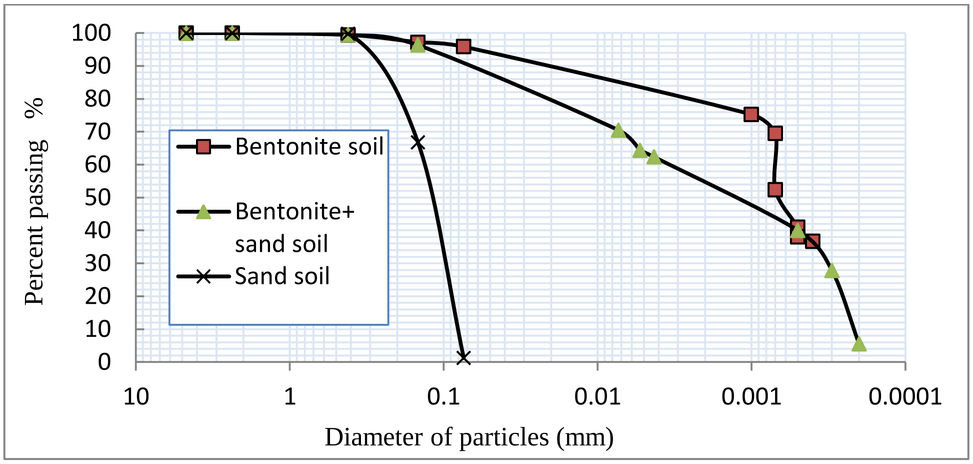

Figure 1. The grain size analysis of soil used.

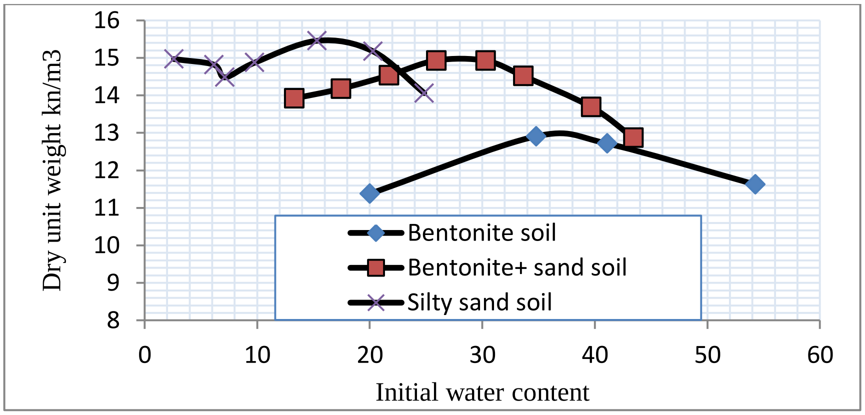

Figure 2. compaction curve of soil used.

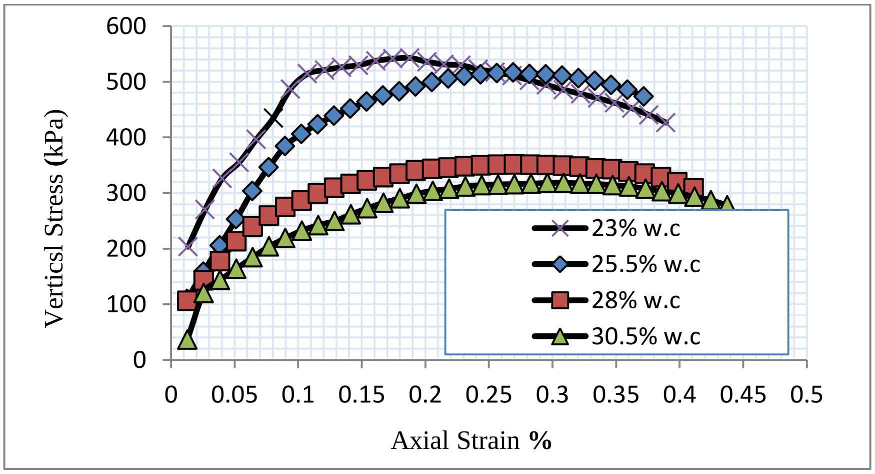

Figure 3. Unconfined compression test results of B-S mixture.

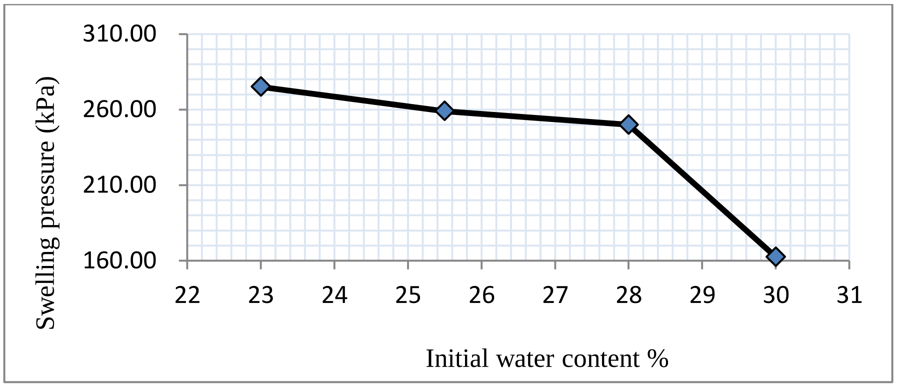

Figure 4. Initial water content versus swelling pressure of B-S mixture.

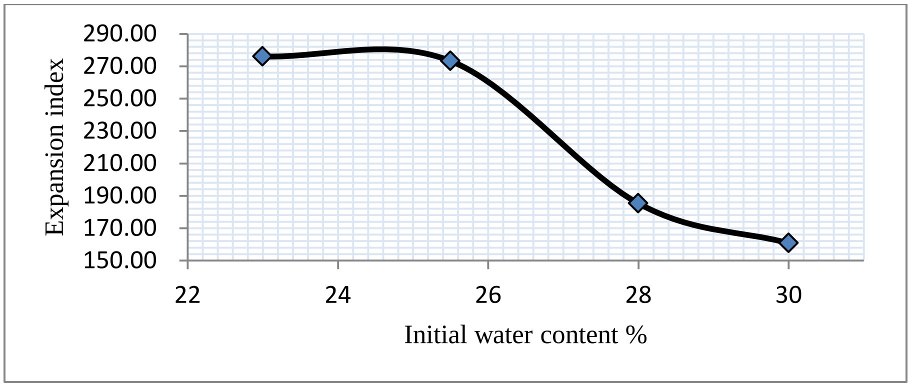

Figure 5. Initial water content versus expansion index.

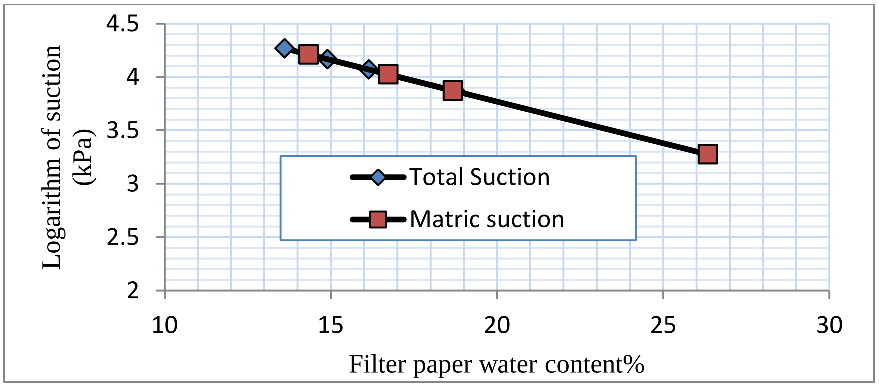

Figure 6. The relation of suction (total and matric) with the filter paper water content.

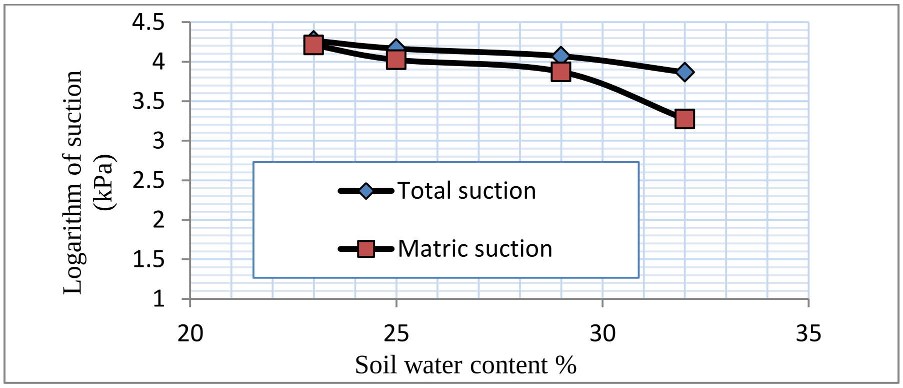

Figure 7. The relation of suction (total and matric) with the soil water content.

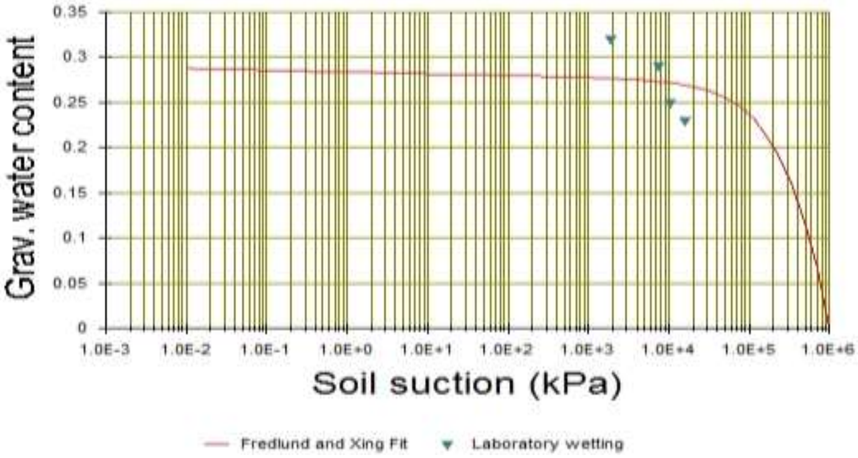

Figure 8. The SWRC estimated by Fredlund and Xing equation.

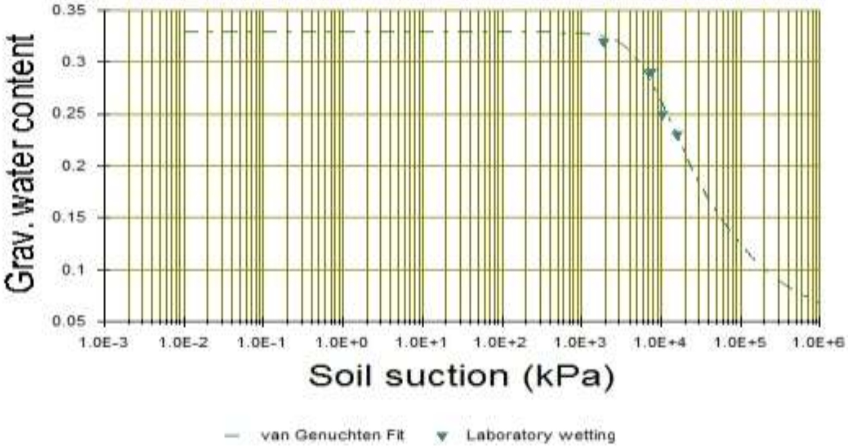

Figure 9. The SWRC estimated by Van-Genuchten equation.

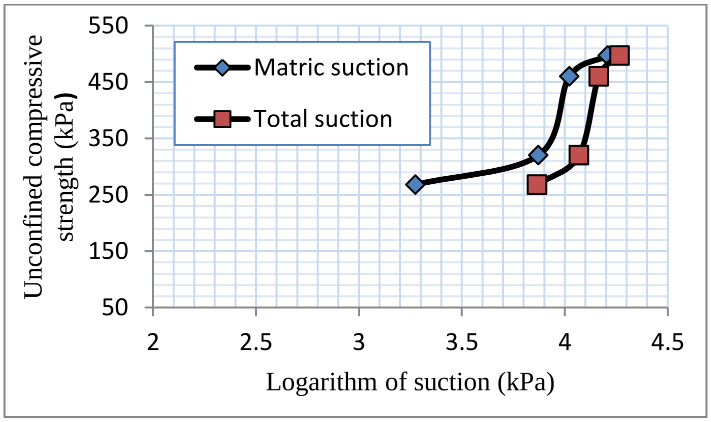

Figure 10. The relation between soil suction (matric and total) and the unconfined compressive strength.