American Journal of Environmental Sciences 1 (1): 34-40, 2005
ISSN 1553-345X

Field and Laboratory Suction- Soil Moisture Relationship of Unsaturated Residual Soils

[1]Bujang B.K. Huat, [2]Faisal Hj. Ali and [2]A. Abdullah
[1]Department of Civil Engineering, University Putra Malaysia
43400 UPM Serdang, Selangor, Malaysia
[2]Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

Abstract: Soils located above the groundwater table such as residual soils are generally unsaturated and possess negative pore-water pressures. A soil-water (moisture) characteristic curve (SWCC) that relates the water content of a soil to matric suction is an important relationship for the unsaturated soil mechanics. The SWCC essentially shows the ability of an unsaturated soil to retain water under various matric suctions. It has a similar role as the consolidation curve of a saturated soil that relates void ratio or water content to effective stress. This study describes a study that has been carried in the field and in the laboratory to examine the suction– soil moisture relationship of unsaturated residual soils of granite and sedimentary rocks origin. The field measurement shows a decreasing trend of suction with depth for both soils. The suction–soil moisture relationship shows two distinct curves, a wetting (sorption) curve and a drying (desorption) curve. While from the laboratory study, it is observed that there is a significant decrease in the soil moisture with increasing suction in the lower suction ranges, until a de-saturation or air entry point for both soils. Beyond this point, the magnitude of the decrease in soil moisture for the equal increment of applied suction is less. The de-saturation point of a particular soil appears to be dependent on the amount of clay content. Higher amount of fines in the soil constitute a more compact particle arrangement and a smaller pore size. Soils with smaller pore sizes de-saturate at higher matric suction.

Key words: Soil Moisture Relationship, Matric Suction, Unsaturated Soil Mechanics, SWCC

INTRODUCTION

The microclimatic conditions in an area are the main factors causing a soil deposit to be unsaturated. Therefore, unsaturated soils or soils with negative pore-water pressures can occur in essentially any geological deposit. An unsaturated soil could be a residual soil, a lacustrine deposit, and soils in arid and semi arid areas with deep ground water table.

Tropical residual soils have some unique characteristics related to their composition and the environment under which they develop. Most distinctive is the microstructure, which changes in a gradational manner with depth. Their strength and permeability are likely to be greater than those of temperate zone soils with comparable liquid limits. Most classical concepts related to soil properties and soil behavior have been developed for temperate zone soils, and there has been difficulty in accurately modeling procedures and conditions to which residual soils will be subjected. Engineers appear to be slowly recognizing that residual soils are generally soils with negative in situ pore-water pressures, and that much of the unusual behavior exhibited during laboratory testing is related to a matric suction change in the soil [1, 2]. There is the need for reliable engineering design associated with residual soils [3].

When the degree of saturation of a soil is greater than about 85%, saturated soil mechanics principles can be applied. However, when the degree of saturation is less than 85%, it becomes necessary to apply unsaturated soil mechanics principles [4]. The transfer of theory from saturated soil mechanics to unsaturated soil mechanics and vice versa is possible through the use of stress state variables. Stress state variables define the stress condition in a soil and allow the transfer of theory between saturated and unsaturated soil mechanics. The stress state variables for unsaturated soils are net normal stress ($\sigma - u_a$) and matric suction ($u_a - u_w$), where σ is the total stress, u_a is the pore-air pressure and u_w is the pore-water pressure. The stress state in an unsaturated soil can be represented by two independent stress tensors as suggested by Fredlund and Morgenstern [5] as follows:

$$\begin{bmatrix} (\sigma_x - u_a) & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & (\sigma_y - u_a) & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & (\sigma_z - u_a) \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \quad (2)$$

Where, σ_x, σ_y, σ_z in equation 1 are the total normal stresses in the x-, y-, and z-directions, respectively; and τ_{xy}, τ_{yx}, τ_{xz}, τ_{zx}, τ_{zy}, τ_{yz} are the shear stresses.

A soil-water (moisture) characteristic curve (SWCC), which relates the water content of a soil to matric suction, is an important relationship for the unsaturated soil mechanics [3]. The SWCC essentially shows the ability of an unsaturated soil to retain water under various matric suctions. It has a similar role as the consolidation curve of a saturated soil that relates void ratio or water content to effective stress. The SWCC of a soil dictates the manner by which the permeability, shear strength and volume change of the soil will behave at different matric suctions upon drying and wetting [2].

This study describes a study that has been carried in the field and in the laboratory to examine the suction – soil moisture relationship of unsaturated residual soils of granite and sedimentary rock origin.

FIELD TEST APPARATUS

For measurement of the field suction, a quick draw tensiometer probe was used. This probe was design to measure soil suction in the field. It is basically a modified ‘jet filled’ tensiometer, portable, and for rugged field use. Figure 1 shows detail of the quick draw tensiometer. Note that the tensiometer can only measure suction up to 1 bar (100 kPa).

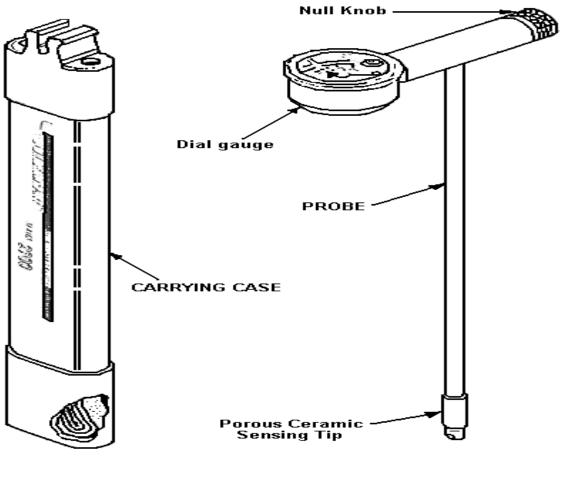


Fig.1: Details of Quick Draw Tensiometer Probe (Soil Moisture Equipment Corp., USA)

LABORATORY TEST APPARATUS

In this study, the suction - soil moisture relationship, which is also known as the soil-water (moisture) characteristic curve (SWCC), is studied in the laboratory by using the modified Rowe cell and modified (double wall) triaxial cell. Samples used in the tests were taken at depth at 0.6m by mean of block sampling in the field of unsaturated residual soil of granite and sandstone (sedimentary) rocks origin.

Modified Rowe Cell: The conventional Rowe Cell was modified and used together with the GDS pressure controllers, using the principles of the pressure plate or axis translation technique [6] for the application of suction.

The modification involved removal of the rubber membrane from the cell top, detachment of the side drainage porous layer, blocking of drainage outlet and the fabrication of a completely new base to include the seating for high air-entry ceramic disc and spiral grooved compartment for flushing the diffused air from below the disc. Figure 2 shows the details of the modified Rowe cell.

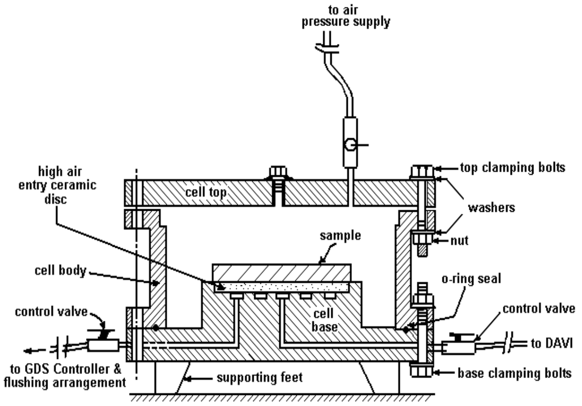


Fig. 2: Modified Rowe Cell

The schematic of the test arrangement is shown in Fig. 3. Air pressure was applied through the top of the cell via valve E. The pore water was applied using the GDS pressure controller with valve 1A open, and with valve 1B and valve 2 closed, to the desired value of suction. The GDS pressure controller records the volume of water flowing in or out of the sample.

The flushing of the diffused air from below the ceramic disc was done using air-water bladder, with valve 1A closed, valve 1B and valve 2 open.

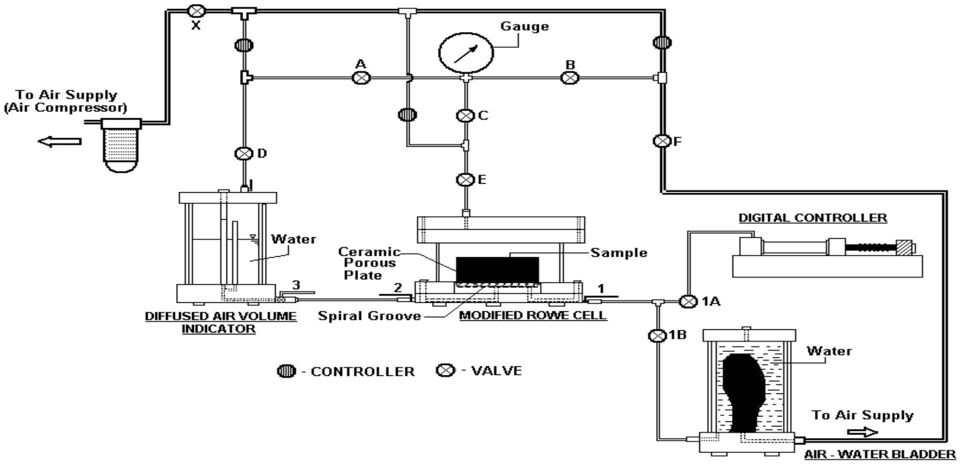


Fig. 3: Schematic Arrangement of Test Setup Using Modified Rowe Cell

The flow of water containing diffused air into the diffused air volume indicator (DAVI) was made possible by creating a pressure gradient between the bladder and the DAVI.

The soil sample, 100mm diameter, 25 mm thick was obtained from a block sample using a split body sampler (Fig. 4) by trimming the height.

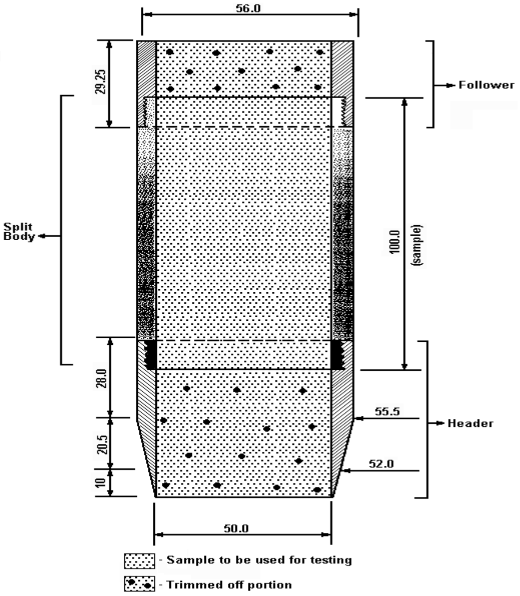


Fig. 4: Split Body Sampler

Modified (Double Wall) Triaxial Cell: A specially modified triaxial cell was also used to study the suction – soil moisture relationship of unsaturated residual soil in the laboratory, in particular the effect of confining pressure.

The typical setup for this test is as shown in Fig. 5. The conventional Bishop-Wesley cell was modified to a specially fabricated double wall cell. One of the two GDS 2 MPa pressure controllers was used for applying and measuring the inner cell pressure, while the other was used to apply and measure the pressure in the annular volume between the outer and inner cell. The design was based on the principle of equal pressure being applied to both sides of the inner and outer wall, thus producing no volume change to the cell.

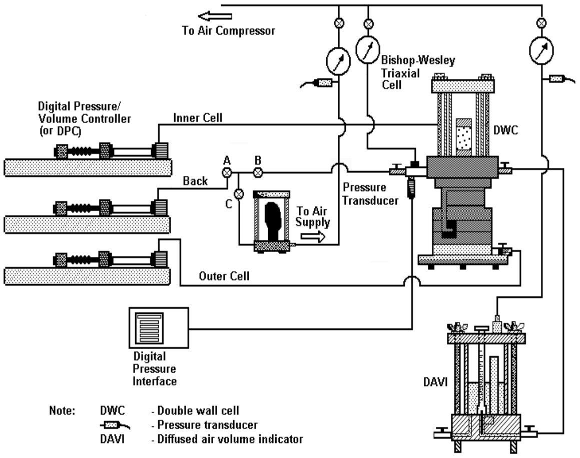


Fig. 5: Schematic Layout of Specially Modified Triaxial Test

Figure 6 shows detail of the double wall cell. The cell comprises of two Perspex cells sandwiched between a top and a bottom metal plates and sealed using appropriate “O”-rings. The seal prevent any movement of liquid from the inner to the outer cell or vice versa. The top and the bottom plates were held in place by four rods screwed onto the bottom plate at one end and a set of nut tightened at the top plate. The whole double

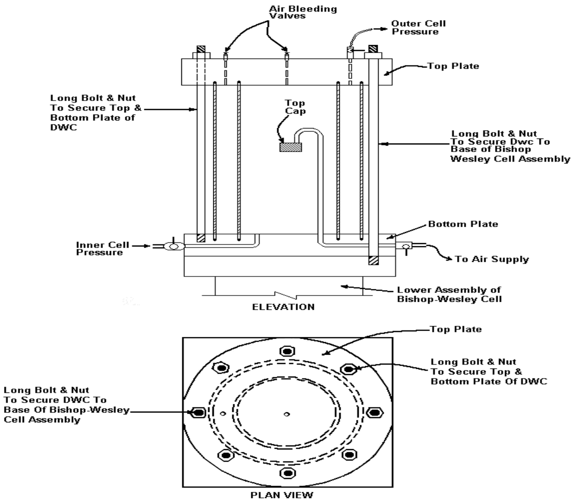


Fig. 6: Details of the Double Wall Cell

wall cell assembly is then fixed to the base of the Bishop – Wesley cell by another set of four rods.

FIELD SITES AND SOIL SAMPLES

Two field sites, namely site A and site B were chosen for this study. Site A was a cut slope at km 31 along the Kuala Lumpur – Karak highway, near Kuala Lumpur, Malaysia. The cut slope basically composed of a residual soil that had developed over the more commonly outcropping Permo-Triassic Mesozonal granite rock of Peninsular Malaysia [7]. Site B was located within the university (University of Malaya, Kuala Lumpur) campus. The soil was that of weathered sedimentary rock of the middle and upper Triassic sequences of sandstone, shale and volcanic rocks.

Table 1: Physical and Index Properties of the Soil Samples

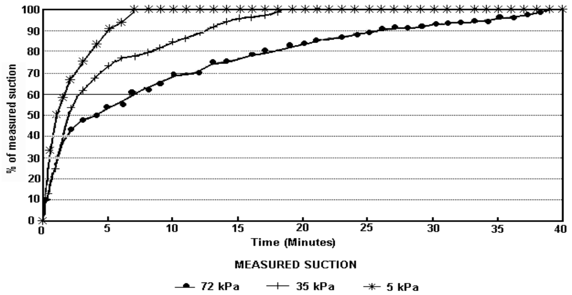
Site	A	B
Weathering Grade/Parent Rock	VI / Granite	VI / Sandstone
Description	Yellowish brown silty clay	Reddish brown sandy clay
Natural moisture Content	22.9 - 26.3%	-
Coefficient of permeability, k	2.5-4.1 x 10^{-8} m/s	-
Liquid Limit	95%	66%
Plastic Limit	45%	32%
Specific Gravity	2.68	2.70
Particle Size		
Distribution:	1.7%	0.5%
Gravel	11.3%	36.8%
Sand	47.0%	27.7%
Silt	40.0%	35.0%
Clay		
Clay Mineral	Kaolinite	Kaolinite and Illite

At both sites field test were done at done of at depth of 30 cm, 45 cm and 60 cm within soil of weathering grade VI, following the general classification of rock weathering of Little [8]. For the laboratory tests, block samples of similar soils were taken at depth of about 0.6 m. Some physical and index properties of the soil samples from both sites are shown in Table 1.

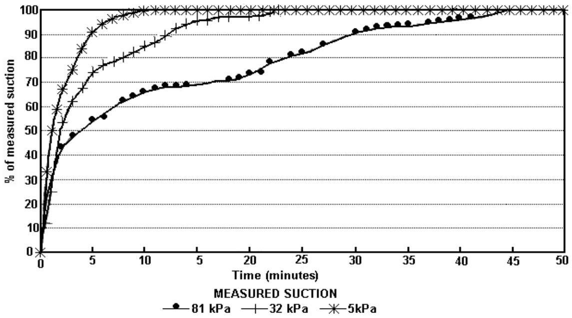
RESULTS AND DISCUSSION

Field Test Results: In the field, the relationship of suction and soil moisture of unsaturated residual soil is studied using the quick draw tensiometer. Data was collected at depths of 30 cm, 45 cm and 60 cm for both the sites A and B. The values of suction recorded for the site A ranges from 5 kPa to 72 kPa, while for the site B, suction values recorded ranges from 5 kPa to 81 kPa, the larger value of suction recorded at the shallower depth (30 cm). A similar observation of suction value decreasing depth was made by Sweeney [9] for Hong Kong soils.

Figure 7 shows the response of suction build up with time for both site A and B. As shown there is a general trend for both the sites, whereby the time required for the higher suction values to stabilize is longer compared to time taken for lower suction values. Data was collected to study the time taken for the suction measured to come to a state of equilibrium. This study would help in judging the appropriate time to stop the measurement, as time taken to reach 100% equilibrium can be quite long.



(a) Site A

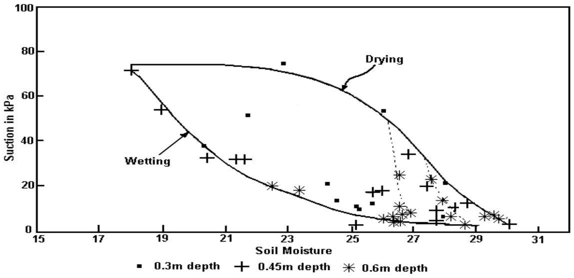


(b) Site B

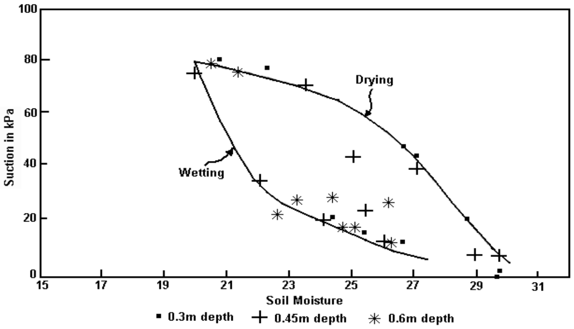
Fig. 7: Suction Build up with Time

The faster response for lower suction could be attributed to the capillary conductivity of the soil. The suction capillary value of a soil decreases with increasing suction. A low capillary conductivity induces a lower transfer rate of water from the probe to the soil, thus increasing the time required for stabilization of the suction reading. The graph can assist in estimating time required for measurement in wet and dry condition.

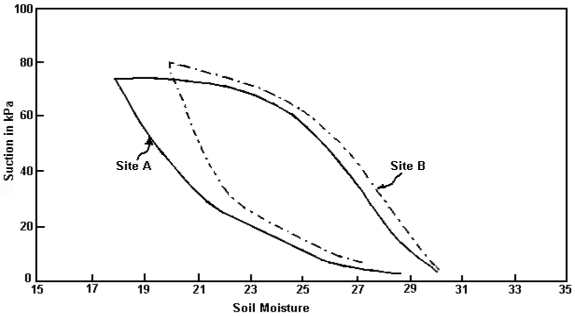
Figure 8 shows the field suction – moisture curves for both site A and B. The data obtained for both sites showed a wide scatter with a marked hysteresis between the wetting and the drying curves.



(a) Site A



(b) Site B



(c) Combined Plot for Site A and B

Fig. 8: Field Suction – Moisture Curve

The upper bound represents the drying curve while the lower bound represents the wetting curve. The wetting curves for both the sites are characteristically concave, showing a rapid decrease in suction for higher suction and leveling off at suction below 20 kPa. The drying curve exhibits a plateau at high suction values and a steeper curve below 60 kPa suction value and possibly levels off below suction value of approximately 5 kPa. The drying (desorption) curve and the wetting (sorption) curve appear to converge at both ends (high and low) suction values.

It is also of interest to note that the suction - moisture curve for site A shows a number of intermediate curves before joining either the drying or wetting curve. These curves can be identified as the initial intermediate curves or scanning curves. The curve following the drying curve initially can be deviated from the upper bound curve due to the effect of moisture content changes, which may explain the considerable scatter in the data. When the moisture content increases the drying curve will no longer be followed but a new wetting curve path would be followed.

Laboratory Test Result: Figure 9 shows plot of suction versus soil moisture obtained using the modified Rowe cell.

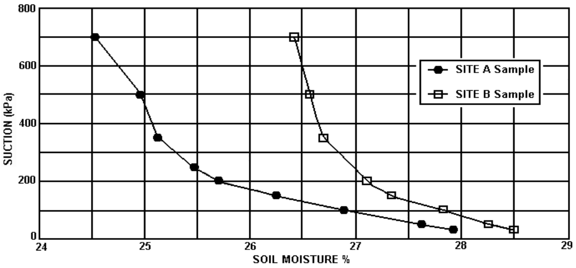


Fig. 9: Laboratory Suction– Soil Moisture using Modified Rowe Cell

A significant decrease in the soil moisture is observed with increasing suction in the lower suction ranges, until a 'de-saturation' or air entry point. After this point, the magnitude of the decrease in soil moisture for the equal increment of applied suction is less. At this stage, the draining of water out of the soil pores becomes more and more difficult. This phenomenon is mainly due to the increasing surface tension force at the contractile layer as the suction increases.

The de-saturation point for the site A sample is approximately at 250 kPa, whereas for the site B sample the de-saturation point was slightly lower, at about 200 kPa. The lower value of site B sample is probably mainly due to soil grading. Site A sample has more clay content than the site B sample (Table 1). Higher amount of fines in the sample constitute a more compact particle arrangement and a smaller pore size. Soils with smaller pore sizes will de-saturate at higher matric suction [10].

In order to study the effect of confining pressure on the suction - soil moisture relationship of unsaturated residual soil, a double wall triaxial cell has been specifically prefabricated for this purpose. Only soil samples of site A were used in this at study. A confining pressure of 400 kPa was applied to the soil sample. The matric suction was first raised to 200 kPa and then reduced to 50 kPa, i.e. the wetting part of the characteristics curve. The drying curve was obtained by increasing back the suction until 250 kPa. The plot of suction and moisture obtained is shown in Fig. 10. In general the shape of the curve obtained is similar to that of the field study (Fig. 8).

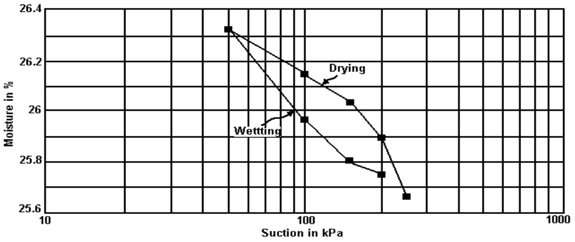


Fig. 10: Laboratory – Moisture Curve (Drying and Wetting) under Confining Pressure of 400kPa (Site A Sample)

The effect of confining pressure on the soil – moisture characteristics curve is shown in Fig. 11. It appears that the confining pressure shifts the curve considerably below the unconfined curve at lower suction level. Both curves however appear to converge at higher suction level, i.e. at approximately the air entry (de-saturation) point for the soil.

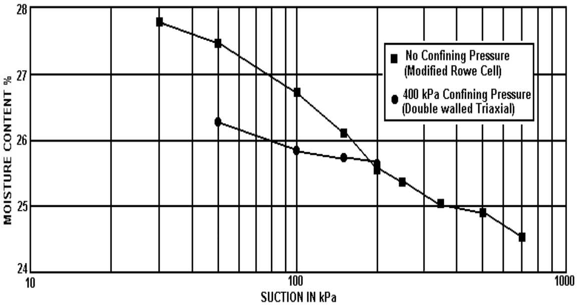
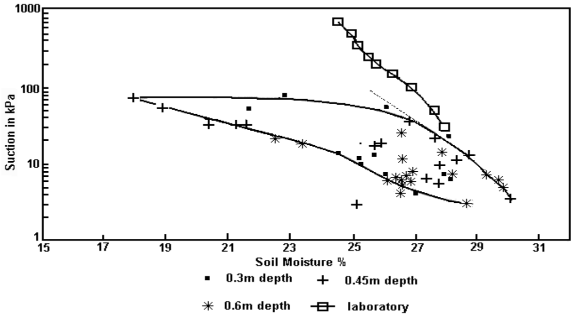
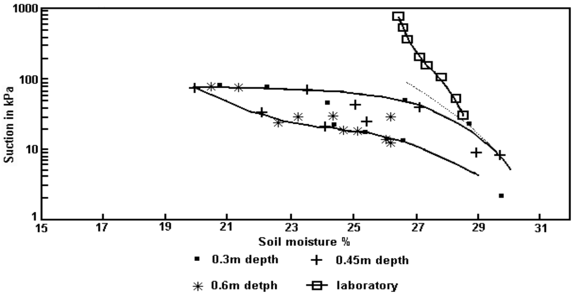


Fig.11: Effect of Confining Pressure on Suction–Moisture Curve (Site A Sample)

Comparison of Field and Laboratory Data: It is always desirable to obtain comparison between the field and laboratory measurements. Figure 12 shows the combined plot of the field (tensiometer), laboratory (modified Rowe cell) suction and soil moisture. While the general shape of the field (wetting) curve is similar to that of the laboratory, but the values of suction at any particular moisture content are of orders of magnitude different. In any case the maximum value of suction measured in the field is not greater than about 100 kPa. Both the field and laboratory curves however appears to converge at low suction values.



(a) Site A



(b) Site B

Fig.12: Combined Field and Laboratory Suction – Soil Moisture

It is of interest to note that such comparisons between this field and laboratory measurements inevitably involve different degree of disturbances that can have a significant influence on the soil behavior.

In the field, the soil has always been under the load from the soil above and confined by its surrounding soil. It has been shown earlier that the confining pressure has an effect in 'pushing down' the suction soil moisture curve. For example as shown in Fig. 11, at moisture content of 26%, the corresponding value of suction at confining pressure of 400 kPa is half that of suction at zero confining pressure. However the de-saturation or air entry points of the confined and unconfined curve are about the same.

CONCLUSION

The field measurement shows a decreasing trend of suction with depth. The suction–soil moisture relationship shows two distinct curves, a wetting (sorption) curve and a drying (desorption) curve. The wetting curve is characteristically concave, showing a rapid decrease in suction for higher suction and leveling off at low suction. While the drying curve exhibits a plateau at high suction values and levels off at low suction. The two curves apparently converge at both ends (high and low) suction values.

From the laboratory study, it is observed that there is a significant decrease in the soil moisture with increasing suction in the lower suction ranges, until a de-saturation or air entry point. Beyond this point, the magnitude of the decrease in soil moisture for the equal increment of applied suction is less. At this stage the draining of water out of the soil pores becomes more and more difficult, which is believed to be due to the increasing surface tension force at the contractile layer as the suction increases.

The de-saturation point of a particular soil appears to be dependent on the amount of clay content. Higher amount of fines in the soil constitute a more compact particle arrangement and a smaller pore size. Soils with smaller pore sizes de-saturate at higher matric suction.

On the effect of confining pressure, it appears that the confining pressure shifts the suction-soil moisture curve considerably below the unconfined curve at lower suction level. Both curves however appear to converge at high suction level, i.e. at approximately the air entry (de-saturation) point for the soil.

When comparing the field and laboratory suction-soil moisture relationship, it appears that the general shape of both wetting curves are similar, but not the value of suction at any particular moisture content.

REFERENCES

1. Fredlund, D.G. and H. Rahardjo, 1985. Theoretical context for understanding unsaturated residual soils behaviour. Proceedings 1st Intl. Conf. Geomechanics in Tropical Laterite and Saprolitic Soils, Sao Paolo Brazil, pp: 295-306.
2. Fredlund, D.G. and H. Rahardjo, 1993. Soil Mechanics for Unsaturated Soils. New York: John Wiley and Sons Inc.
3. Ali, F.H. and H. Rahardjo, 2004. Unsaturated Residual Soil. Chapter 4 in Tropical Residual Soils Engineering. Huat *et al*., (Eds.). Leiden. Balkema, pp: 57-71.
4. Fredlund, D.G. and H. Rahardjo, 1987. Soil mechanics principles for highway engineering in arid regions. In soil mechanics considerations: Arid and semiarid areas. Transportation Research Record, 1137: 1–11.
5. Fredlund, D.G. and N.R. Morgenstern, 1977. Stress state variables for unsaturated soils. J. Geotechnical Engineering Division, ASCE, 103: 447–466.
6. Hilf, J.W., 1956. An investigation of pore pressure in cohesive soils. US Bureau of Reclamation. Technical Memorandum. No. 654.
7. Raj, J.K., 1985. Characterization of the weathering profile developed over porphyritic biotite granite in Peninsular Malaysia. Bull. Intl. Assoc. Eng. Geol., Paris, 32: 121-127.
8. Little, A.L., 1969. The engineering classification of residual tropical soils. Proceedings 7th Intl. Conf. Soil Mechanics Foundation Engineering, Mexico, 1: 1-10.
9. Sweeney, D.J., 1982. Some *in situ* soil suction measurements in Hong Kong's residual soil slopes. Proceedings of 7th S.E.A.G.S. Conf., Hong Kong, 1: 91-106.
10. Croney, D. and J.D. Coleman, 1954. Soil structure in relation soil (pF). Soil Sci., 5: 75-78.