SOIL-WATER CHARACTERISTICS CURVES FOR RESIDUAL REDDISH BROWN SOIL

(CASE STUDY OF UNIVERSITY OF BENIN, BENIN-CITY, EDO STATE, NIGERIA)

BY

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FACULTY OF ENGINEERING
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A SECOND M.ENG SEMINAR SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTERS DEGREE (M.Eng.) IN GEOTECHNICAL ENGINEERING
THE DEPARTMENT OF CIVIL ENGINEERING,
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JUNE, 2019

CERTIFICATION

This is to certify that this work was carried out by OLUWATOKI, Abiodun Ebenezer with MAT. NO. PG/ENG/1512270, of the Department of Civil Engineering, University of Benin, Benin City, Edo State, Nigeria.

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DEDICATION

This work is dedicated to the Almighty God, for his unlimited love, grace, provision and guidance upon me and my entire family.

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ABSTRACT

The soil water characteristic curve (SWCC) is a graphical relationship between the matric suction (pore water suction) ψ and the water content (gravimeter ω or volumetric θ or degree saturation s). It is one of the basic characteristics of unsaturated soils and as such, it is useful for estimating the other properties of soil when solving engineering problems in areas like fluid flow, irrigation scheduling, compressibility and shear strength. SWCC also provide input to the design of a compacted clay cover liner and earth Dam due to its potential impact of flow rate and the dessication processes. Since the experimental procedures, in which a filter paper or pressure plate test adopted for determining the matric suction-water content relationship is time consuming and cost-intensive, hence the need to produce the SWCC using some mathematical functions (models).

The fundamental aim of this research is to determine the mechanical behaviour of lateritic soil using SWCC. The soil samples that were used in this research work are residual reddish brown lateritic soil that was obtained from University of Benin Campus. The method of disturbed sampling was employed in obtaining soil samples for laboratory testing. Full laboratory investigation were carried out on the soil samples, these include; liquid limits, plastic limit, plasticity index, liquidity index, specific gravity, particle size analysis and specific gravities. Soil water characteristics curve (SWCC) specimens were prepared with one compactive effort (BSL) to relative OMC. 2.5kg of each specimen was moistened with tap water, mixed thoroughly and compacted in BS moulds and later cored into stainless steel rings with inside diameters of 50mm and heights of 50mm with the aid of a mallet. Each of the 15 specimens was covered with caps at both ends before saturation. The samples were subjected to full saturation by capillary action for a period of 3 weeks. The pressure plate drying test used in this study was conducted to determine the relationships between volumetric water content and matric suction potentials in a soil subjected to pressures ranging between 0 - 1500kPa. Pressure was applied to a predetermined value to induce matric suction. Testing was terminated when the outflow stopped indicating that specimens had equilibrated with the applied matric suction. The specimens were removed and their volumetric water content was determined. The procedure was repeated to develop an entire SWCC by subjecting the soil specimens to different pressures (0 – 1500kPa). In this study, the author used 3 models and they are Van Genuchten equation, Fredlund and Xing equation and Brooks – Corey equation. With the data from the pressure plate extractor to predict hydraulic productivity and volumetric water content of the soil samples.

The results of index properties shows that the natural moisture content of the soil is between 36%- 46%, plasticity index is between 17,92% to 28.03%. The specific gravity is between 2.31%-2.57% and the soil is classified as lateritic soil of low plasticity. The SWCC data from pressure plate extractor have been fitted with Van Genuchten (1980); Brooks-Corey (1964); Fredlund and Xing (1994) equation. The result show that the air entry value and residual matric suction for residual soils are in the range of 18kpa to 30kpa and 43kpa to 670kpa respectively.The result shows that: Generally, Van Genuchten and Brooks-Corey models over predicted volumetric water content (θ) at low suctions, while Fredlund-Xing model under predicted it but the values are close to laboratory measured values.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

Unsaturated soil mechanics has become a necessary tool for analyzing the behaviour of soils in the vadose zone and the flux boundary conditions as required in many geotechnical and geo-environmental problems (Fredlund and Rahardjo, 1993a). Compacted natural soils used as hydraulic barriers in waste containment facilities such as engineered landfills are often unsaturated and modeling of flow and transport through these soils require the knowledge of their unsaturated hydraulic properties. It is the water content versus matric suction relationship which becomes an important additional relationship in qualifying unsaturated soil behaviour (Fredlund and Rahardjo, 1993b).

The soil-water characteristics curve (SWCC) defines the relationship between (pore water suction) matric suctions (ψ) and water content [gravimetric (w) or volumetric (θ) or degree of saturation (S)] (Tinjum et al., 1997). The soil – water characteristics can be described as a measure of the water holding capacity (i.e. storage capacity) of the soil as the water content changes when subjected to various values of suction. The soil-water characteristics is a conceptual and interpretative tool through which the behaviour of unsaturated soils can be understood. As the soil moves from the saturated state to drier states (unsaturated states), the distribution of the soil, water and air phases change as the stress state changes. The relationships between these phases take on different forms and influence the engineering properties of unsaturated soils (Fredlund and Rahardjo, 1993a; Fredlund, 1996; Vanapalli et. al. 1999).

The relationship between pore water suction and water content, as presented in a SWCC is one fundamental relationship used to describe unsaturated behaviour of a soil. Suction is inversely proportional to the water content in a soil. Suction generally increases as the soil desaturates. Increasing suction generally results in high resistance to flow and increase in effective stress. Desiccation is a by-product of the increased effective stress (Miller et al., 2002). Increasing suction in compacted clays due to decrease in water content modifies the flow behaviour of covers. During desiccation, the saturation of a liner is reduced and the remaining pore water is held at increasingly large suction. The relationship between saturation and suction during desiccation is described using the SWCCs. Knowledge of suction and corresponding water content in the soil can be used to predict cracking potentials of liners. The onset and resulting amount of cracking can be correlated to a soil-specific critical suction level (Miller et al., 1990). Hence, the SWCC provides critical input to the design of a compacted clay cover liner due to its potential impact on flow rates and the desiccation process.

A typical SWCC is shown in Figure 1. Several defining parameters of the curve include the matric suction which correspond to the break in the curve (near the saturated water content, θs) is referred to as the air entry suction (ψa). This air entry suction corresponds to the matric suction required to remove water from the largest pores (Brooks and Corey, 1966). The water content corresponding to the asymptote of the SWCC at low degrees of saturation is called the residual water content (θr). It is also the degree of saturation, or gravimetric water content, or volumetric water content beyond which it becomes increasingly difficult to remove water from a specimen by drainage.

At zero water content the soil matric suction is appropriately 1,000,000 kPa (Fredlund et. al., 1994). This dry condition is achieved by oven drying the soil. It is necessary to define the residual state of saturation hydraulic conductivity (Brooks and Corey, 1964; van Genuchten, 1980).

The shape of the SWCC is a function of the soil type. Soils with smaller pores have higher air entry pressure (ψa). Soils with wider ranges of pore sizes exhibit greater changes in matric suction with water content (Hillel, 1980; Fredlund and Rahardjo, 1993a). The SWCCs of compacted clay soils depend on the compaction water content, compactive effort and plasticity index (Tinjum et al., 1997). Several models have been used to describe the SWCC, commonly used one includes the Brooks-Corey (1964); van Genuchten (1980); Fredlund and Xing (1994); and these were reviewed by Leong and Rahardjo (1997a). The three most common models are the Brooks – Corey equation (Brooks and Corey, 1964, 1966) , van Genuchten equation (van Genuchten 1980) and Fredlund and Xing equation (Fredlund and Xing 1994) These three models have been used in this work to describe the unsaturated behaviour of the test soils and various correlations between geotechnical properties and SWCC of samples were investigated and analyzed and their hydraulic productivity (Ku) were predicted alongside with their volumetric change in order to determine their suitability for landfill application and earthdam construction.

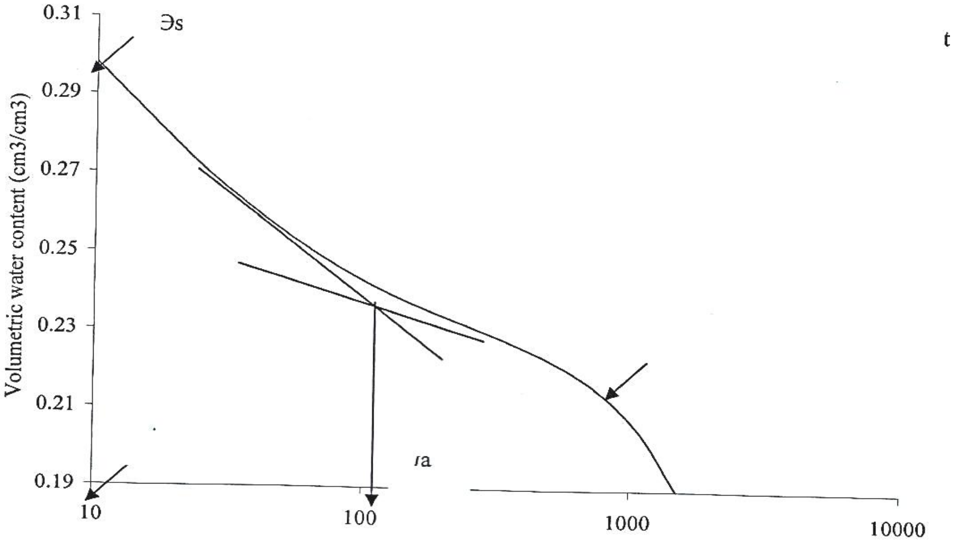


Figure 1: Typical Soil Water Characteristics Curve Osinubi, K.J and Bello A.A, (2011)

The Brooks-Corey model is expressed as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{\psi_a}{\psi}\right)^{\lambda} \quad \psi \geq \psi_a \qquad (1.1)$$

Θ =1 and $\theta = \theta_s$ where $\psi < \psi_s$

Where Θ is a normalized, dimensionless volumetric water content; and λ = a fitting parameter called the pore-size distribution index, θ_s is the saturated volumetric water content, θ_r is the residual volumetric content, θ is the actual volumetric water content (Corey, 1994).

The Van Genuchten model is expressed as:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{\frac{1}{[1 + (\alpha\psi)^n]}\right\}^m \qquad (1.2)$$

Where α, n and m are fitting parameters and m is equal to 1 – n-1. α = soil parameter related to the air entry value of “bubbling pressure”; parameter m, rotates the sloping portion of the curve. As *m* increases, the range of the curve between ψa and the knee (the point of inflection at the lower portion of the curve as it approaches a horizontal position) of the SWCC decreases. The parameter is the pivot point of the curve and its value is related to the value of the air-entry suction. As a increases, the air- entry suction increases. The parameter *n* controls the slope of the SWCC about the pivot point, which occurs at normalized volumetric water content (Θ) of 0.5. As n increases, the sloping portion of the curve between ψa and the knee of the SWCC becomes steeper (Miller et al., 2002). Each of these parameters is described by Leong and Rahardjo (1997a, b).

Equations describing the SWCC have been classified into three-parameter and four-parameter equations while the classification of SWCC equations into unimodal and bimodal SWCC functions are presented by Burger and Shackelford (2001). Dual porosity models are also available (Burger and Shackelford, 2001). Thus, other models are those of McKee and Bumb (1984, 1987).

The factors which influence the SWCC of soils include texture, structure and clay mineralogy (Williams et al., 1983), compaction energy (Marinho and Stuermer, 2000), as well as stress state (Ng and Pang, 2000). Many researchers (Arya and Paris, 1981; Arya et al., 1999a, b; Fredlund et al., 2000) have shown that the SWCC of soil can be predicted from grain size distribution (GSD) function as well as other soil index properties. Zapata et al. (2000) showed that the SWCC, whether measured or estimated, is highly variable. The variability of SWCC and the associated uncertainty is viewed to have some effect on any model for unsaturated soil behaviour that makes use of this relationship.

The soil-water characteristic curve, SWCC, has become a valuable tool for the estimation of unsaturated soil property functions, USPF, in geotechnical engineering practice. At the same time, indiscriminate usage of the estimation techniques for unsaturated soils can lead to erroneous analytical results and poor engineering judgment. Soils that undergo significant volume changes as soil suction is changed constitute one situation where erroneous estimations can occur. In particular, it is the evaluation of the correct air-entry value for the soil that has a significant effect on the estimation of subsequent USPFs (Fredlund, 2002; Fredlund and Rahardjo, 1993).

1.2 STATEMENT OF PROBLEM

The study of unsaturated hydraulic conductivity of soil is of great importance to aid in adequate designed and construction of engineering facilities such as in landfill system and earthdam. For instance, compacted clay liner and cover systems are mostly unsaturated in the field. The study of the unsaturated hydraulic flow of fluid within such system can only be achieved by determining the unsaturated hydraulic conductivity.

The study of unsaturated hydraulic conductivity can be achieved in the field which is very expensive, hence the use of numerical models. The need to determine the suitability of lateritic soil for such purposes at various depths is vital in other to assess its fitness. Soil-water characteristic curves are usually generated from the laboratory experiment. Parameters obtained from the curves are imputed in to some forms of mathematical equations to determine the unsaturated hydraulic conductivity and volumetric water content over the entire suction range.

1.3 AIM AND OBJECTIVES

The aim of this research is to determine the unsaturated hydraulic conductivity and volumetric water content over the entire suction range.

The specific objectives include

1. To determine SWCC of lateritic soil using traditional experiments
2. To determine the geotechnical properties of unsaturated laterite soil.
3. Use the three models to predict the volumetric change of unsaturated residual soil using SWCC
4. To establish the relationship between unsaturated soil moisture and soil suction over a range of 0 to 1500kpa of lateritic soils.
5. The use of the models for predicting hydraulic conductivity of lateritic soils using SWCC.

1.4 SCOPE OF STUDY

SWCC curves were developed for 15 samples of lateritic red earth soils obtained in Benin City, Edo State. Standard laboratory procedures for obtaining SWCC was employed. Tests were accompanied by mechanical and physical tests of samples to obtain their geotechnical properties. Various correlations between geotechnical properties and SWCC of samples were investigated and analyzed and their hydraulic productivity (Ku) were predicted alongside with their volumetric change in order to determine their suitability for landfill application and earthdam construction.

1.5 SIGNIFICANCE OF STUDY

Given the apparent increasing use of compacted fine-grained soils as barriers, which primarily are based on consideration of availability of material and cost and the favourable results obtained by Osinubi and Nwaiwu (2004) on the use of laterite soil as hydraulic barrier material, considering methods of achieving a greater level of hydraulic performance with this locally abundant soil will be a worthwhile engineering research effort.

Furthermore, most barrier technologies presently in use were developed in the temperate regions, adopting such technologies for application in the tropics may not be practical and cost effective as there are significant differences in geological, environmental and material properties in the two regions. In order to develop or reliably adopt suitable and cost effective liner technology for tropical environment, geoenvironmental assessment of tropical soils such as lateritic soils has to be undertaken.

Another important applications for the SWCC proposed in this thesis work is in pavement design; where the unsaturated soil mechanics plays an important role in the performance of the pavement structure, mainly on the resistance and deformation of the soil. These characteristics of the soil are mainly due to variations in matric suction, which could take place due to changes on external conditions especially due to presence of water, changes in temperature, depth of the ground water table, external loads, etc. This relationship between the matric suction and the amount of water into the soil has been considered in the Enhanced Integrated Climatic Model (EICM) as part of the Mechanistic– Empirical Pavement Design Guide (MEPDG).

The SWCC obtained will be used for most tropical soils. Confirmation of the best model equation for SWCC which will be invaluable to geotechnical investigation for laterite soils.

CHAPTER TWO

LITERATURE REVIEW

2.1 THE PATH FORWARD

There are two approaches that could be taken with regard to further refinement in the application of the SWCC in unsaturated soil mechanics (Figure 2.1). First, it is possible that modified laboratory test procedures be developed and used for the measurement of the amount of water in the soil versus soil suction relationships in geotechnical engineering. It is also possible that new laboratory test equipment be designed to more realistically simulate field conditions. Second, it is possible that an additional, independent test be performed that would assist with the interpretation of a conventional gravimetric water content SWCC. An independent laboratory test that can be performed is a "shrinkage curve" test. The shrinkage curve test provides a fixed relationship between the gravimetric water content and the instantaneous void ratio of the soil. The authors would suggest that both of the above-mentioned approaches be given consideration (D.G. Fredlund and S.L. Houston, 2013).

A review of the research literature shows that modified apparatus for geotechnical applications have already become a trend for measuring the SWCC. Alternate testing procedures have also been proposed in the research literature. In particular, the need for a modification to the determination of an appropriate SWCC has arisen in situations where the soil changes volume as soil suction is changed. The development of testing apparatus that measure the SWCC under controlled suction and net normal stress, along with volume change measurements, is appealing for many geotechnical engineering problems (i.e., left branch in Figure 2.1). The approach that suggests adding a shrinkage test to assist in the interpretation of the SWCC (i.e., right branch in Figure 2.1), blends in well with the procedures that have already been used in engineering practice as well as agriculture-related disciplines.

In other words, the existing laboratory test procedures associated with the SWCC would continue to be used; or available data sets used, however, greater care needs to be taken in the interpretation and application of the results in engineering practice. This approach may be particularly appealing when net normal stress is relatively low in the field application.

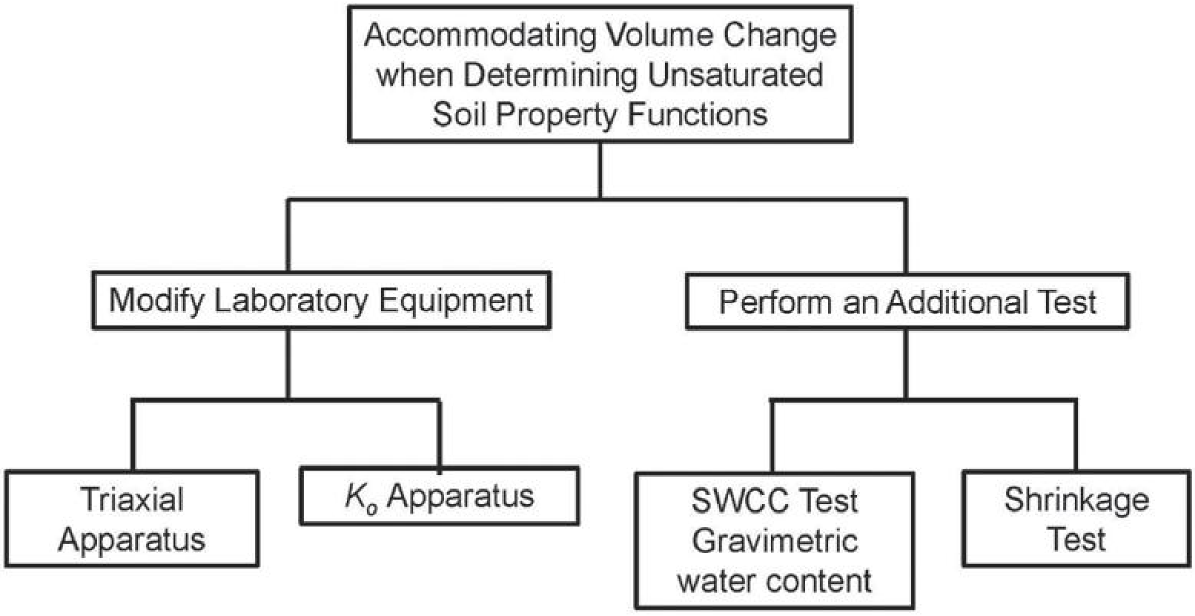


Figure 2.1: Approaches that can be taken to accommodate volume changes associated with soil suction changes(D.G. Fredlund and S.L. Houston, 2013).

2.2 Reddish Brown Lateritic Soils

The fundamental characteristic of these soils is the nature and constitution of the mineral soil mass. Generally, they are surface formations in tropical and subtropical areas which are enriched in sesquioxides of Iron (Fe_2O_3) and or Aluminum (Al_2O_3) and develops by intensive and long lasting weathering of the underlying parent rock. This enrichment/concentration may be by residual accumulation or by solution movement or chemical precipitation (Maignien, 1966; Gidigasu, 1976; Charman, 1988; Fookes, 1997). In all cases, it is the result of secondary physicochemical processes and not the normal primary process of sedimentation, metamorphism, volcanism or plutonism. The accumulated hydrated oxides are sufficiently concentrated to affect the character of the deposit in which they occur. They may be present alone in an unhardened soil, as a hardened layer or as a constituent such as concretionary nodules in a soil matrix or a cemented matrix enclosing other materials (Charman, 1988).

2.3 Formation of lateritic soils.

Lateritic soils are formed in hot, wet tropical regions with an annual rainfall between 750mm to 2000mm (usually in areas with a significant dry season) on a variety of different types of rocks with high iron content. The location on the earth, that characterize these conditions fall between latitude 35S and 35N (Maigien, 1966; Newill and Dowling, 1970; Gdigasu, 1975; Fookes, 1997). Laterization involves physico-chemical alteration of primary rock forming minerals into materials rich in 1: 1 lattice clay minerals (kaolinite) and laterite constituents

(Fe, Al, Ti, Mn). In the first place Ca, Mg, Na and K are released, leaving behind a siliceous framework consisting of silica tetrahedral and alumina octahedral. Silica which is soluble at all pH values, will be leached slowly while as alumina and ferri sesquioxides (Al_2O_3, Fe_2O_3 and TiO_2) remain together with kaoline as the end product of clay weathering. The end result is a “reddish matrix” made from kaolinite, goethite and fragments of the pisolitic iron crust (Maignien, 1966; Gidigasu, 1976; Charman, 1988; Fookes, 1997). Two aspects of the parent rock affect the formation of laterite. One is the availability of iron and aluminum minerals. These are more readily available in basic rocks. The other is the quartz content of the parent rock. Where quartz is a substantial component of the original rock, it may remain as quartz grains. Laterite profiles occur on flat slopes in the terrain where runoff is limited. On the level ground, where drainage is poor, expansive clay dominate at the expense of laterite. From the above, three major stages have been identified in the process as follows (Maignien, 1966; Gidigasu, 1976):

- **Decomposition**: - Physicochemical breakdown of primary minerals and the release of constituent elements (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O etc) which appear in simple ionic forms.

- **Laterization**: - Leaching under appropriate conditions of combined silica and bases and the relative accumulation or enrichment of oxides and hydroxides of sesquioxides (Fe_2O_3, Al_2O_3 and TiO_2). The soil conditions under which the various elements are rendered soluble and removed through leaching or combination with other substances depend mainly on the pH and Eh of the groundwater and the drainage conditions. The level to which the second stage is carried depends on the nature and the extent of the chemical weathering of the primary minerals. Under conditions of low chemical and soil forming activity, the physico-chemical weathering does not continue beyond the clay forming stage and tends to produce end products consisting of clay minerals predominantly represented by kaolinite and occasionally by hydrated or hydrous oxides of iron and Aluminum.

- **Desiccation or Dehydration**: **-** The partial or complete dehydration (sometimes involving hardening) of the sesquoxide rich material and secondary minerals. The dehydration of colloidal hydrated iron oxide involves loss of water and the concentration and crystallization of the amorphous iron colloids into dense crystals in the sequence; limonite, goethite, with haematite to hematite. Dehydration may be caused by climatic changes, upheaval of the land, or may also be by human activities for example by clearing of forests.

2.4 Global distribution of lateritic soils

Laterites and lateritic materials are widely distributed throughout the world but occur more frequently in the tropics and subtropics of Africa, Australia, India, South-east Asia and South America (Maignen, 1966). The global distribution of laterite and associated materials is broadly governed by world climatic zones. Lateritic formation requires conditions of temperature and rainfall similar to those of the humid tropical and subtropical zones. There are other factors peculiar to particular regions which govern the type of laterite which may be found, whether an indurated hardpan laterite, a nodular laterite or some other form. These factors include local variations in climate and the geology as well as the geomorphology associated with the weathering and soil development stages of landscape formation (Gidigasu, 1975).

2.5 Chemical and mineralogical composition

Clay mineralogical constitution of this soil is principally kaolinite often mixed with quartz. The higher proportion of sesquioxdes of iron (Fe_2O_3) and aluminum (Al_2O_3) relative to other chemical components is a feature characteristic of all grades of lateritic soils. Those groups in which the iron oxide predominates are called ferruginous laterite soils and those in which alumina predominates - aluminous laterite soils. Iron is present usually as oxide minerals 54 notably haematite (Fe_2O_3) and also as hydrated oxide – goethite (FeOOH) or as limonite (an amorphous mixture of hydrated oxides which retain various amounts of water). Aluminum occurs as its hydrated oxides gibbsite ($Al_2O_3.3H_2O$) and/or boehmite ($Al_2O_3H_2O$). It is also contained within the lattice structure of kaolinite as an Aluminum silicate. Lateritic soils may contain significant amounts of manganese often identifiable as black nodules or concretions while titanium occur in limited quantities as titanium oxides. Zinc, chromium, nickel, cobolt, molebdenium, vanadium and other trace elements have been identified. Free silica is present as quartz inherited from the parent material. The predominant clay mineral is well crystallized kaolinite.

2.6 Colour

Lateritic soils have characteristic reddish shades, which appear to be due to the various degrees of iron oxides – goethite and hematite, titanium and manganese hydration. The shades also reflect the degree of maturity. Generally, lateritic soils derive their colour from two sources.

- From organic matter: Black, brown, grey
- From mineral composition:

(a) Iron: red, orange, yellow, brown, blue and green.
(b) Calcium, Magnesium, Sodium and Potassium: White
(c) Aluminum: White
(d) Manganese: Black, Brown.

2.7 Geotechnical properties of lateritic soils.

Geotechnical characteristics and field performance of lateritic soils as well as their reaction to different stabilizing agents may be interpreted in the light of all or some of the following parameters.

- Genesis and pedological factors (parent material, climate, topography, vegetation, period of time in which the weathering processes have operated).
- Degree of weathering (decomposition, sesquoxide enrichment and clay size content, degree of leaching).
- Position in the topographic site and
- Depth of site in the profile (Gidigasu, 1976).

2.8 Particle size distribution

The particle size distribution of the soil may provide the following information-

(a) A basis for identification and classification of the soil
(b) The compactibility characteristics
(c) Permeability
(d) Sweallability and
(e) A rough idea of deformation characteristics of the soil mass.
(f)

Texturally, lateritic soils are very variable and may contain all fraction sizes; boulders, cobbles, gravel, sand, silt and clay as well as concretionary rocks. Quartzitic gravels which are formed from the alteration of quartz rich parent rocks are generally well graded with 20% of silt and clay – size fraction. Concretionary laterites have a higher content of fines ranging between 35 - 40%. Foot slope concretionary laterite gravels are coarse and gap graded (less sand), compared to high level gravels (Gidigasu, 1976).

2.9 Plasticity characteristics of lateritic soils

The interaction of the soil particles at the microscale level is reflected in the consistency limits or Atterberg limits of the soil. Knowledge of the Atterberg limit may provide the following information.

- A basis for identification and classification of a given soil
- Texture
- Strength and compressibility characteristics
- Swell potential of the soil or the water holding capacity.

Plasticity may be affected by pretest preparation, degree of moulding and time of mixing, drying and rewetting and irreversible changes in plasticity on drying. Drying drives off adsorbed water which is not completely regained on rewetting (this is the case in both oven and air drying, Fookes, 1997). Soil which contain hydrated oxides of iron and aluminium may become less plastic on drying. This is partly because dehydration of sesquoxides creates a stronger bond between the particles which resists penetration by water. Studies on the relationship between the natural moisture content and liquid limit and plastic limit have shown that generally the natural moisture content is less than the plastic limit in normal lateritic soils (Vergas, 1953). However, the lateritic soils from higher rainfall areas may have moisture contents as high as the liquid limit (Ackroyd, 1971).

2.10 Compaction characteristics of lateritic soils

The compaction characteristics are determined by their grading characteristics and plasticity of fines. These in turn can be traced to genetic and pedological factors. A significant characteristic of lateritic soils is the influence of the strength of the concretionary coarse particles on compaction. Most lateritic soils contain a mixture of quartz and concretionary coarse particles, which may vary from very hard to very soft. The strength of these particles has major implications in terms of field and laboratory compaction results and their subsequent performance in service. Weak coarse fractions breakdown under load with a resulting increase in fines of the soil (Ackroyd, 1971). The degree to which the materials breakdown is related to the content of iron oxide and the degree of dehydration. The higher the iron oxide content and the more the degree of dehydration, the harder the concretionary particles become. Placement variables (moisture content, amount of compaction, and type of compaction effort) also influence the compaction characteristics. Varying each of these placement variables has an effect on permeability, compressibility, swellability, strength and stress – strain characteristics (Lamb, 1958).

2.11 Strength properties of lateritic soils

Lateritic soils are weathered under conditions of high temperatures and humidity with well-defined alternating wet and dry seasons and continually leached by rainwater causing a tendency for deterioration of its strength characteristics. Shear strength characteristics of these soils have been found to depend significantly on the parent materials and the degree of weathering (ie degree of decomposition, laterization and desiccation) which is a function of the position of the sample in the soil profile and the compositional factors (Lohnes *et al.*, 1971; Wallace, 1973). The higher the degree of laterization, the more favourable are the shear strength parameters (Baldovin, 1969). Furthermore, the structural elements in the soils are often a less stable coarse-grained aggregation of variable strength which may break down in performance (Maigien, 1966; Charman, 1988) in addition to their varying silt and clay content which often render them moisture sensitive. (Ola, 1978; Nicholson *et al.*, 1993). The aforementioned properties give an indication of their engineering limitations that restrict its use and of such sites to minor engineering projects.

2.12 Permeability of lateritic soils

Lateritic soils are distinguished from other soils by the presence of high proportion of sesquioxides of iron (Fe_2O_3) and aluminum (Al_2O_3) relative to other chemical components. The sesquoxide gel within the fine fraction of the soil tends to coat the surface of individual soil particles. This coating reduces the surface activity of the clay mineral (principally kaolinite often mixed with quartz) and by extension the ability of the clay mineral to absorb water. It also causes a physical cementation of adjacent grains that result in the aggregation of particles to form coarser particles and a reduction in surface activity (15 m^2/g) and ability of the clay particles to absorb water. This factor also contributes significantly in lowering the plasticity of the soil and the inability of the soil to achieve very low hydraulic conductivity. The Base Exchange capacity of the clay mineral is usually very low (~5 meq/100g). Both factors reduce plasticity (Maigien, 1966; Townsend *et al.*, 1971; Charman, 1988; Rowe *et al.*, 1995) and invariably the ability of the soil to achieve low hydraulic conductivity.

2.13 Stabilization of lateritic soils

Stabilization may be defined as any processes by which a soil material is improved and made more stable. The goals of stabilization are therefore to improve the soil strength, to improve the bearing capacity and durability under adverse moisture and stress condition, and to improve the volume stability of a soil mass. The tendency for lateritic gravels to be gap graded with depleted sand fraction and to contain a variable quantity of fines as well as to have coarse particles of variable strength which breakdown, limits their usefulness in some engineering projects such as road pavement (Charman, 1988). To ameliorate the above deficiencies and consequently to improve on their field performance characteristics, they need to be stabilized.

2.13.1 Mechanical stabilization

Strength and durability of soils can be improved by mechanical means using compaction without the addition of any foreign matter. Water is added during compaction to displace air and facilitate movement of fine grained particles past one another so as to achieve densification.

2.13.2 Cement stabilization

Most soils including tropical and lateritic soils can be stabilized with cement. Depending on the soil type, 4% to 10% of cement by weight of dry soil is mixed with the soil to cause it to harden into a compact mass, which will not soften in the presence of water. Cementation is based on hydration of cement. The major hydration products are a series of calcium silicate hydrates (CSH) and hydrated lime Ca(OH)2. Reactions of the soil with cement include replacement of Ca^{2+}, adsorption of $Ca(OH)_2$ by particles and cementation at interparticle contacts by the CSH gel. When clay graded minerals are present in excess of about 30%, it is more difficult to achieve economic stabilization by use of cement due to great difficulty in pulverizing and mixing (Gillot, 1968). The success of stabilization depends on intimate mixing of the additive with the soil. For lateritic soils, thorough pulverization is important because the sesquoxides effectively coat the surfaces of particles and can prevent the necessary chemical reaction taking place.

2.13.3 Lime stabilization

Lime is generally considered more appropriate for the stabilization of more clayey soils, but is less effective in organic soils. Lime stabilization is achieved with calcium oxide (quicklime) or calcium hydroxide (slaked lime). The stabilization mechanism of lime is similar to that of cement. Lime acquires silica or other pozzolans in the soil to form CSH gel. Lime reduces plasticity by replacing troublesome cations such as sodium with calcium. At the same time, coagulation takes place and the coarser lime particles absorb a good deal of free water resulting in dehydration. Lime treatments of 3% to 8% by weight of dry soil are typical for improvement of plastic and expansive soils.

2.13.4 Bitumen stabilization

In bituminous stabilization, bitumen materials (hot cutback and emulsions) or road tars are mixed with soil so as to water proof the particles and/or provide the additional cohesion necessary for stabilization. The amount of binder normally ranges between 4 and 7%.

2.14 UTILIZATION OF LATERITIC SOILS IN CIVIL ENGINEERING

Originally, lateritic soil utilization was discussed in connection with mining of solid minerals such as Iron, Aluminum, Bauxite, and Manganese (Maignien, 1966). The civil engineering aspect has also been the subject of numerous studies and has been successfully used in various civil engineering construction projects as foundation materials, highway embankments, earth dams, low cost (mud) houses and in making bricks, etc. In the tropics and subtropics, the most common pavement material is ironstone lateritic gravel (Osinubi and Katte, 1997). Sometimes these soils require improvement in their engineering properties before they can be used in any form of construction. In such cases, lateritic soils can be chemically treated with suitable stabilizing agent.

2.15 EXAMPLES OF VOLUME CHANGE AS SOIL SUCTION IS CHANGED

The conventional application of the SWCC for the estimation of unsaturated soil property functions commences with the assumption that the soil does not significantly change volume as soil suction is increased. This assumption may be reasonable for low compressibility sands, silts and dense coarse grained soils. However, there are other situations where the geotechnical engineer must determine unsaturated soil property functions when the soil undergoes considerable volume change with changes in soil suction. Such applications include wetting and drying of expansive clays, wetting of collapsible soils, and drying of slurry materials.

A common situation where extreme volume change occurs in the soil as soil suction is increased, involves the drying of initially wet or slurry materials. Sludge material and slurry material (e.g., Mature Fine Tailings, MFT, from the Oil Sands operation), are deposited at water contents well above the liquid limit of the material (e.g., w = 100%). The material is deposited in ponds and allowed to dry in order to increase its shear strength. The geotechnical engineer is called upon to undertake numerical modelling simulations of the drying process. Volume changes in excess of 100% are common, and failure to take volume change into consideration yields erroneous results during the drying simulation.

Almost any situation where a soil starts under very wet conditions and is subjected to drying will result in significant volume change. The material may be initially saturated and may remain near saturation, as soil suction increases during the drying process. Estimation procedures that have historically been proposed for the calculation of unsaturated soil property functions assume that a decrease in water content corresponds to a decrease in the degree of saturation of the soil. This may not always be the case and consequently the estimation procedures will give erroneous results when either gravimetric water content or volumetric water content SWCCs are used to calculate unsaturated soil properties such as the permeability functions.

Expansive soils problems are often associated with the soil taking on water as a result of infiltration. This is an adsorption process that involves the wetting SWCC. The effect of hysteresis needs to be taken into consideration as well as the effect of volume changes that occur as the soil dries or goes towards saturation. Collapsible soils follow a different drying stress path than wetting stress path. The collapsible soil may initially be in a relatively dry state with substantial soil suction. As the soil imbibes water the volume of the soil decreases (or collapses). This has been a difficult stress path to simulate through numerical modelling. Volume change as soil suction is decreased has an effect on the determination of suitable unsaturated soil property functions.

This paper mainly focuses on the estimation of suitable SWCCs for soils that have high initial water content. At the same time it is recognized that there may be other stress paths that might need to be simulated in geotechnical engineering practice. This research also discusses the benefits that can be accrued through use of modified pressure plate apparatuses for the measurement of the SWCC.

2.16 DESCRIPTION OF SWCC TEST PROCEDURES COMMONLY USED IN GEOTECHNICAL ENGINEERING

The purpose for which the SWCC laboratory results are used in geotechnical engineering is quite different from that of the agriculture disciplines and as a result, questions arise as to whether it is necessary to change the SWCC test procedure, the interpretation procedure or both. This paper shows that application of the SWCC in geotechnical engineering is somewhat different from applications in agriculture, primarily because soil volume change in response to wetting and loading for many geotechnical engineering applications can be substantial.

Test procedures that had been used in agriculture for several decades began to be used in geotechnical engineering subsequent to 1960 (Fredlund, 1964). The need to measure the SWCC became apparent when it was realized that changes in the suction of a soil produced an independent effect on soil behavior from changes in total stress. Engineering problems associated with expansive soils provided the initial impetus for understanding swelling soil behavior in terms of changes in soil suction. In most cases, the expansive soils had substantial clay content and underwent considerable volume change during the swelling process associated with wetting. In addition, subsequent applications of matric suction resulted in a decrease in the volume of the soil specimens. There are other applications of unsaturated soil mechanics in geotechnical engineering that involve soil volume change due to change in soil suction. Examples involve the drying of initially slurry materials and the wetting of collapsible soils. For drying of initially slurried soils there can be extremely large volume changes associated with the application of soil suction.

The primary application of SWCCs in geotechnical engineering has been for the estimation of unsaturated soil properties such as permeability function (i.e., hydraulic conductivity versus soil suction) (e.g., Fredlund et al., 1994; van Genutchen, 1980), and the shear strength function, (i.e., shear strength versus soil suction) (e.g., Vanapalli et al., 1996; Fredlund et al., 1996). The estimation of realistic hydraulic conductivity functions depends on the separation of volume changes that might occur while the soil remains saturated from volume changes that occur as the soil desaturates.

Conventional testing procedures adopted within soil physics have not made a clear distinction between these two volume change mechanisms. Direct acceptance and adoption of soil physics SWCC testing procedures can result in serious deficiencies when testing materials that undergo volume change as soil suction is increased. Stated another way, it is not sufficient to measure changes in the mass of volume or water removed from the soil between various applied soil suctions. Rather, it is necessary to quantify the amount of volume change that occurs and to separate the volume changes that occur while the soil remains saturated from the volume changes (and water content changes) that occur as the soil desaturates. The estimation procedures for unsaturated soil property functions is different when the soil is undergoing volume change from the situation where there is no volume change as soil suction is changed.

The differences in physical processes associated with the two types of volume change give rise to the need to be able to measure both changes in the volume of water mass as well as actual (or instantaneous) volume changes of the soil specimen.

Two approaches to addressing this need for volume change measurements are considered in this paper. The first approach considers modifying the laboratory SWCC apparatuses such that the volume of the soil specimens is measured during the test. Devices that have been developed to meet this need are discussed later in this paper. The second approach suggests using an independent test to measure the relationship between gravimetric water content and void ratio. The required laboratory test is referred to as a shrinkage test and details related to this procedure are subsequently outlined in this paper.

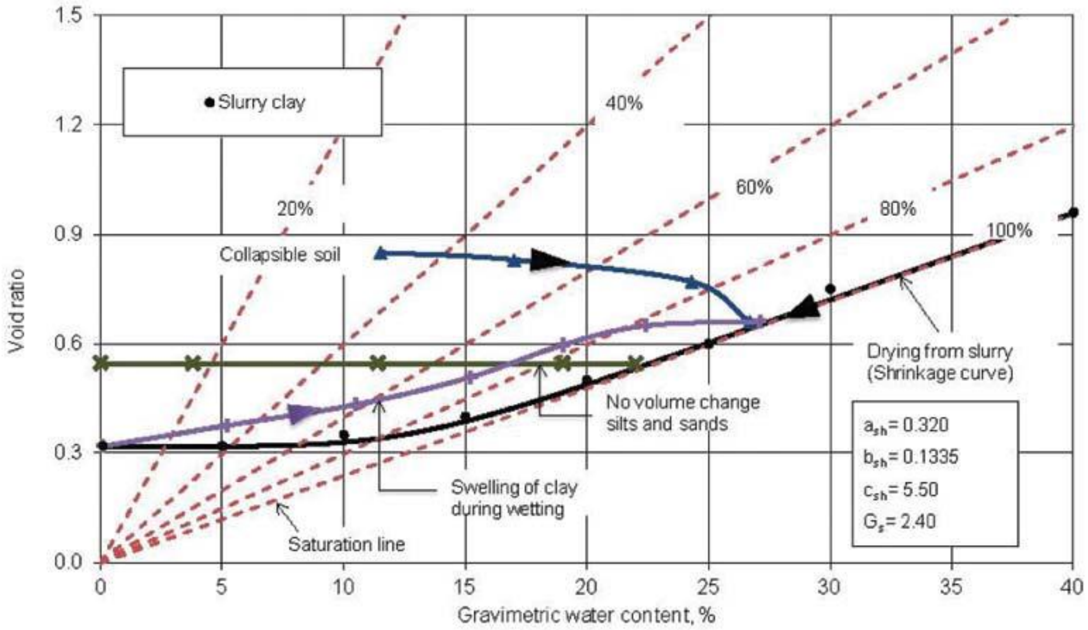


Fig. 2.2: Volume-mass pathways for a variety of possible geotechnical engineering situations (D.G. Fredlund and S.L. Houston, 2013).

The shrinkage curve can be experimentally measured from initial high water content conditions to completely dry conditions. A digital micrometer can be used for the measurement of the volume at various stages of drying as shown in Figure 4. Brass rings can be machined to contain the soil specimens (i.e., the rings have no bottom). The rings with the soil can be placed onto wax paper and can be dried through evaporation to the atmosphere. The dimensions of the soil specimens are appropriately selected such that cracking of the soil is unlikely to occur during the drying process.

Figure 2.3. Digital micrometer used for the measurement of the diameter and thickness of shrinkage specimens. (D.G. Fredlund and S.L. Houston, 2013)

The initial dimensions selected for the shrinkage curve specimens used in this study were a diameter of 3.7 cm and a thickness of 1.2 cm. The mass and volume of each soil specimen can be measured once or twice per day. Four to six measurements of the diameter and thickness of the specimen were made at differing locations on the specimens. It has been observed that as the specimen diameter began to decrease, with the specimen pulling away from the brass ring, the rate of evaporation increased significantly (i.e., about twice as fast).
The increase in the evaporation rate is related to the increased surface area from which evaporation occurs. Consequently, it is recommended that the measurements of mass and volume be increased to once every two to three hours once the material shows signs of pulling away from the sides of the ring. The "shrinkage curve" can be best-fit using the hyperbolic curve proposed by Fredlund et al., (1996, 2002). The equation has parameters with physical meaning and is of the following form:

$$e(w) = a_{sh}\left[\frac{w^{c_{sh}}}{{b_{sh}}^{c_{sh}}} + 1\right]^{\left(\frac{1}{c_{sh}}\right)} \quad - \quad - \quad - \quad - \quad - \quad - \qquad (2.1)$$

where: a_{sh}= the minimum void ratio (e_{min}), b_{sh} = slope of the line of tangency, (e.g., = e / w when drying from saturated conditions), c_{sh} = curvature of the shrinkage curve, and w = gravimetric water content. The ratio, $\frac{a_{sh}}{b_{sh}} = \frac{G_s}{s}$ is a constant for a specific soil; G_s is the specific gravity and S is the degree of saturation.

Once the minimum void ratio of the soil is known, it is possible to estimate the remaining parameters required for the designation of the shrinkage curve. The minimum void ratio the soil can attain is defined by the variable, a_{sh}. The b_{sh} parameter provides the remaining shape of the shrinkage curve. The curvature of the shrinkage curve around the point of desaturation is controlled by the c_{sh} parameter.

2.17 PREVIOUS WORK DONE

Zhang et al. (2018) carried out a research on the estimation of soil-water characteristic curve for cohesive soil with methylene blue value (MBV). 15 different cohesive soil was used in their research, a soil-water characteristic curve (SWCC) relationship between MBV, plasticity index (PI) of the soil and the percentage passing sieve no 200 (P_{200}) was generated using Fredlund and Xing's model and the pressure plate test, these parameters was used to generate a regression equation for the determination of four fitting parameters. They observed that from the SWCC the slope parameters of the curve *bf* are associated with the moisture susceptibility of the cohesive soils, which means that the lower the MBV/PI/P_{200} the lower the suction and the higher the MBV/PI/P_{200} the higher the suction for the same degree of saturation of the different soils. They finally concluded that the results obtained from the SWCC and regression equation that P_{200} and PI are positively related to MBV which indicates that higher clay mineral content corresponds to higher PI or MBV, which means that MBV can also be used to describe the moisture susceptibility of cohesive soil. Although they advised for a wider ranges cohesive soil to modify the formula in a further research, but from the result they were able to show that the difference in the pressure plate test result and the prediction method using the MBV was acceptable.

Khalid and Ahmed, (1973) researched on the determinations of unsaturated soil parameters using experimental procedures, and they observed that using experimental procedures are time consuming, their work was majored in the use of indirect method for the determination of different parameters, which is the use of soils with difference plasticity limit, index and gradation. The SWCC uses these parameters in terms of the gravimetric water content and degree of saturation against the soil matric suction, these was done in other to determine the relationship between the PI, P_{200} and the SWCC. From their research it was observe that the mathematical model analyzed by Frelung and Xing give a good agreement with the experimental result. They also observed that there is an agreement between the experimental result obtained and the equation obtained from the model using linear regression when related to the degree of saturation (S), liquid limit (LL), plastic limit (PL), plastic index (PI), % passing sieve 200 (P_{200}) and metric suction (SU kPa)

Fredlund, (2002) researched on the use of Soil –Water Characteristic Curve in the Implement of Unsaturated Soil Mechanics and the result of his research was that:
Soil-water characteristic curve is having an increasingly important role in the assessment of unsaturated soils property functions. The procedures being proposed are approximate but are satisfactory for analyzing many unsaturated soil mechanics problems. It is important that there be as much consistency as possible with respect to the measurement and interpretation of the data measured in the laboratory. This paper attempts to bring greater consistency into the geotechnical application of soil-water characteristic curve data, and the research concluded that, it is anticipated that there will be an increase in research related to the use of the soil-water characteristic curve data for the estimation of unsaturated soil property functions. There are numerous assumptions and limitations related to the use of estimated unsaturated soil property functions. It is important that geotechnical engineers be aware of the pitfalls and assumptions inherent in the applications of unsaturated soil mechanics theories.
Fredlund and Houston (2013) researched on the interpretation of soil-water characteristics curves when volume change occurs as soil suction is changed, they describe the characteristics of a high volume change material and then proceeds to describe how the SWCC laboratory results can be properly interpreted with the assistance of a shrinkage curve. Two laboratory data sets was presented and used to illustrate how the test data should be interpreted in the case of high volume change soils. In their research there was also developments in the design of SWCC laboratory equipment with the result that both overall volume change and water content change can be monitored when measuring SWCCs and this means that from the results all volume-mass properties can be calculated. The researchers concluded that changes in the volume of the soil specimens as soil suction is increased can significantly affect the interpretation of soil-water characteristic curve information, and that water storage function can be obtained by differentiating the instantaneous volumetric water

content SWCC with respect to soil suction. This is true for suction values less than and greater than the air-entry value of the soil.

Yusuf, et al (2018) they carried out research to determine the SWCCs of unsaturated tropical soils, they carried out the test on five different residual soil and observed that the air entry value and residual matric suction for residual soils are in the range of 17 kN/m^2 to 24 kN/m^2 and 145 kN/m^2 to 225 kN/m^2 respectively and from the fitting curve of their result it is found that the average value of the Fredlund and Xing parameters such as a, m and n are in the range of 0.24 – 0.299, 1.7 – 4.8 and 0.142 – 0.440 respectively.

Qian and Rahardjo (2012) researched on the determination of soil-water characteristics curve variables. His research finding shows that Soil–water characteristic curve (SWCC) contains the fundamental information needed for describing the mechanical behavior of unsaturated soil. Some parameters such as air-entry value, slope at the inflection point, residual water content and residual suction are commonly used to describe the SWCC and other associated properties such as shear strength and permeability. Currently these parameters are determined using the graphical method which can be subjective and time consuming. Equations for determining these parameters was proposed and the relationships between SWCC parameters and fitting parameters was discussed in his research. The equations he obtained can be used for computational analyses to replace the conventional graphical method in providing consistent results.

2.18 DIFFERENT DESIGNATIONS FOR THE AMOUNT OF WATER IN THE SOIL

There are three primary ways to designate the amount of water in the soil; namely, gravimetric water content, volumetric water content and degree of saturation. Each designation has a role to play in understanding the physical behaviour of unsaturated soils.

2.18.1 Gravimetric Water Content

The measurement of water content in the laboratory is generally first measured in terms of gravimetric water content, *w*, because the mass of water is the easiest variable to measure. Other designations are then computed based on the volume-mass relations. The gravimetric water content SWCC was presented.

2.18.2 Volumetric Water Content (Initial Volume)

It is possible to write the volumetric water content referenced to the initial volume of the soil; however, it should be noted that this designation has little or no value in unsaturated soil mechanics. Only under conditions of no volume change during suction change does the equation become equal to the instantaneous volumetric water content SWCC.

2.18.3 Void Ratio

The void ratio versus soil suction is of value in some situations. One such situation occurs when attempting to describe volume changes while the soil remains saturated under an applied suction. The void ratio can be written as a function of gravimetric water content which is a function of soil suction.

2.18.4 Experimental and parametric study program on the effect of volume changes on the interpretation of the SWCC

The effect of volume change on the interpretation of SWCCs was studied using the results from two experimental studies. For both soils, the laboratory SWCCs and shrinkage curve measured on initially slurried soils. The two materials were: (1) Oil Sands Tailings referred to as MFT (Mature Fine Tailings), and (2) Regina clay. The laboratory test results are first presented followed by a parametric study that focuses on the significance of overall volume change as soil suction is increased.

A parametric study was also undertaken for each of the two materials. The parametric study involved changing two of the fitting parameters in the gravimetric water content SWCC. For the Oil Sands Tailings, the first break in curvature along the gravimetric water content SWCC, (referred to as *w Break*), was maintained constant. For the Regina clay soil, the air-entry value, AEV, determined from the degree of saturation SWCC was kept constant.

In each case, an empirical construction procedure involving the intersection of two straight lines on a semi-log plot was used to determine a single number for the break in curvature (Vanapalli et al., 1999).

2.19 EQUIPMENT MODIFICATIONS TO MEASURE OVERALL VOLUME CHANGE

Equipment in common use for measuring this soil water characteristic (Tempe cell, pressure membrane, pressure plate), often lacks some features that are important to the study of unsaturated soil behavior for geotechnical applications. These features involve a means to apply field-appropriate net normal stress, the determination of volume change as well as water content change (during drying and wetting), and the use of a single specimen for determination of the relationship of soil suction to the volume-mass soil properties. Several research groups have recently developed modified pressure plate-type devices. One such apparatus that allows for testing of the complete SWCC on a single specimen is the modified oedometer (*Ko*) device (Padilla et al., 2005; Pham et al., 2004). Soil suction is controlled using the axis-translational method, on a pressure plate cell. A *Ko* SWCC device manufactured by GCTS, Tempe, AZ, is shown in Figures 23 and 24. Some of the features of the GCTS *Ko* cell include the simulation of field net normal stress (e.g., overburden plus structural loads), measurement of water released or absorbed from the specimen during the test, capability of tracking the vertical deformation of the soil specimen, and the capability of obtaining several points along the soil-water characteristic curve without dismantling the cell (Perez-Garcia et al., 2008). The ceramic high-air-entry disk, head, used in this apparatus is epoxied into a ring that is fitted into a recess on the bottom base plate.

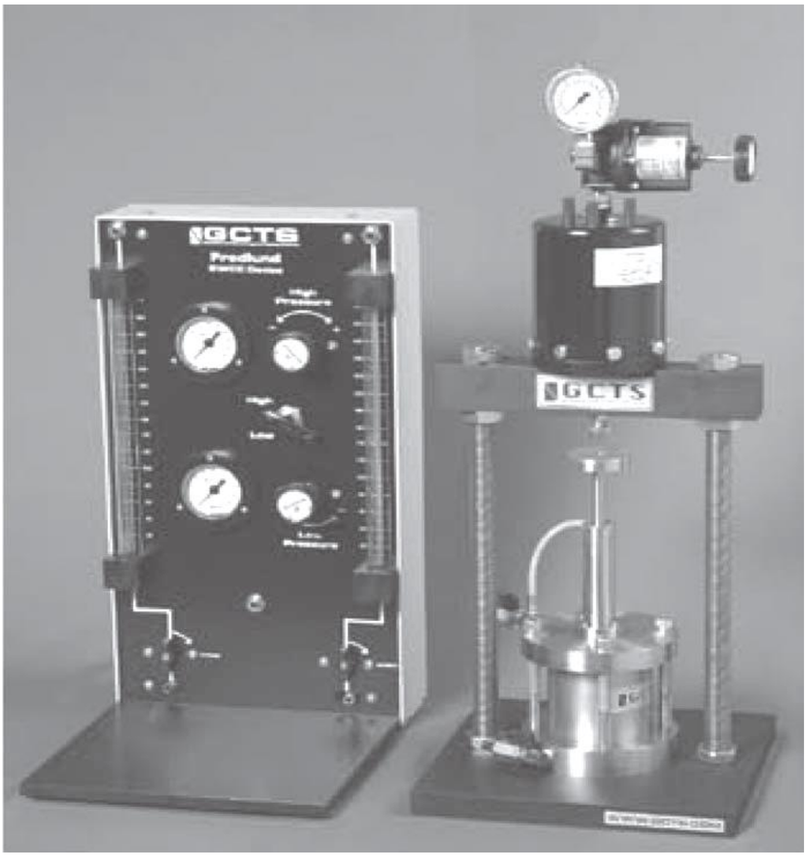


Figure 2.3: GCTS Pressure plate device (D.G. Fredlund and S.L. Houston, 2013).

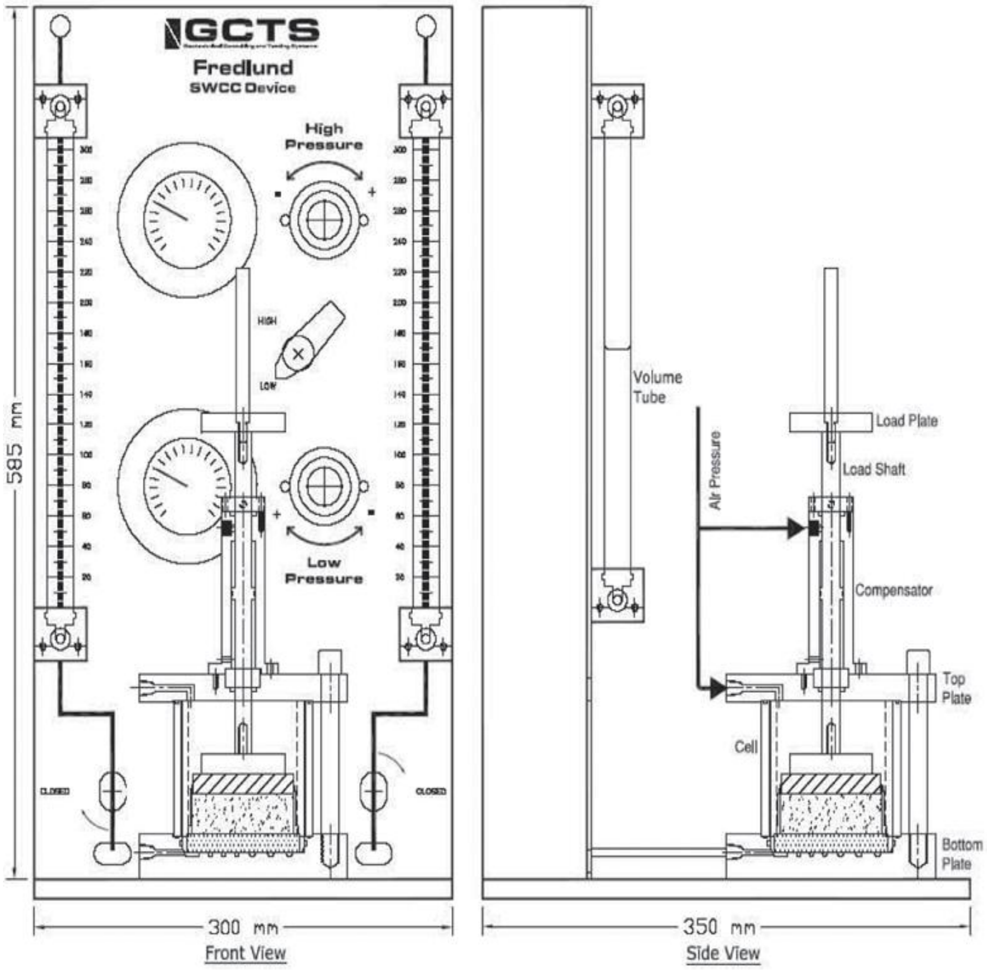


Figure 2.4: GCTS Pressure plate device. (D.G. Fredlund and S.L. Houston, 2013).

The disk has a grooved water compartment to keep the disk saturated and to facilitate the flushing of diffused air. The base has two external ports that connect the water compartment to the drainage system consisting of two graduated volumetric tubes. Each tube has a graduated scale with 1 mm marks. The volume tube measurements can be read to the nearest mm, which translates to accuracy in volume measurements of 0.07 cc. The application of the net normal stress is accomplished with a loading rod inserted from the top of the device and dead weights placed on top of the loading plate. Alternatively, a loading frame can be used to apply loads directly to the loading rod. The application of a vertical load also ensures close contact between the sail specimen and the ceramic disk in addition to more closely simulating field conditions.

A stiff, stainless steel specimen ring is used to constrain the specimen laterally. Compacted or undisturbed specimens with diameters from 50 to 75 mm and 25 mm high can be tested in this device. The platen and the loading rod move up or down with the sample as the sample expands or compresses, and this measurement is tracked with a dial gage or LVDT. A pressure compensator is also provided to null the uplift loads generated when applying pressures inside the cell. The same air pressure applied to the cell is also applied to a piston which has a net area equal to the cross-sectional area of the loading rod.

The axis-translational technique allows the control of negative pore water pressures less than zero-absolute, and consists of elevating the pore-air pressure such that the desired matric suction, (u_a – u_w), is achieved. The saturated head used in the axis-translational technique, when saturated, allows the passage of water yet prevents the flow of air up to a value of air pressure corresponding to the air-entry-value of the ceramic disk. One of the main problems associated with high air-entry ceramic disk is the diffusion of air that accumulates over time in the water compartment beneath the head. For this reason, the device has been designed to allow for flushing air from beneath the head.

Accumulation of air results in the apparent volume of water coming out of the specimen being larger than actual. If water is going into the sample, diffused air will prevent the water from flowing into the specimen if the amount of air is sufficient to retard the water conductivity through the high air entry disk (Padilla et al., 2006). Measured rates of air diffusion as a function of suction for several 15 bar stones are shown in Figure 25. For 15 bar ceramic disks, the diffusion of air at 700 kPa is about 0.9 cc/day and 1.8 cc/ day at 1,400 kPa. The amount of diffused air is relatively small when applying low suctions but the rate of air diffusion increases more or less linearly as the air-entry-value of the head is approached (Perez, 2006; Perez-Garcia et al., 2008).

2.20 Measurement of Unsaturated Flow Properties of Soil

In the design, operation and maintenance of landfills and other waste containment facilities, it is generally assumed that the barrier material is saturated throughout its entire life span; which in reality is not, as barrier system is mostly unsaturated due to the percolation of precipitation through the waste during the inactive and post closure period (Khire et al., 1995; Tinjurn et al., 1997; Chin and Shackelford, 1998; Miller et al., 2002: Osinubi and Nwaiwu, 2002). In view of this, the logy of the compacted soil barrier should be based on the unsaturated flow through the soil since it is normally unsaturated when compacted. In contrast to a lining system, exposure and interaction of landfill cover with different environmental and atmospheric conditions allow the persistence of unsaturated condition (Benson, 2000). Therefore, right prediction and measurement of the movement of contaminants and unsaturated water through the compacted soil is a function of the intrinsic knowledge of the unsaturated hydraulic behaviour of compacted soil (Chiu and Shackelford, 1994; Wang and Benson. 1995).

Applications where unsaturated flow are needed include designing of earthen caps for waste containment facilities, assessment of containment teaching in the unsaturated zone, and predicting containment migration rates. 1hc unsaturated properties and behaviour of compacted black cotton soil treated with cement kiln dust must be well understood for better quantification, prediction and performance of the soil-cement kiln dust mix as a suitable barrier material in waste containment application.

The measurement of hydraulic conductivity in unsaturated soils (unsaturated conductivity) is difficult to obtain, partly due to its variability in the held, excessively time-consuming process as the duration of the test increases with decreasing water content of the soil and very expensive (Kasim et al., 1999). For these several models (Brooks and Corey, 1964; van Genuchten, 1980; Fredlund and Xing, 1994, etc.) were reviewed by Leong and Rehardjo (1997a). Models by Richard et al. (2001), Neuweiler and Cirpka (2005); Borgesen et al. ('2006) and Matthews et al (2010) were developed for calculating the unsaturated hydraulic conductivity from more easily measured soil water characteristics curve using the saturated coefficient of as an initial value.

Generally, there are two methods of measuring unsaturated hydraulic conductivity of soils; direct and indirect measurements. The direct measurement includes steady state and unsteady state methods (Leong and Rahardjo, 1997b; Kasim et. al., 1999).

a) **Steady State Methods**: Matric suction is imposed first on a soil specimen using the axis translation technique (Fredlund and Rahardjo, 1993; Benson and Gribbs, 1997). Equilibrium is attained by constant water content, and then a hydraulic gradient is imposed across the soil specimen. The flow rate is then measured and the permeability is obtained through Darcy's (1856) law.

b) **Unsteady State Method or Instantaneous Profile Method**: A cylindrical specimen is subjected to a continuous flow of water from one end. The hydraulic gradient and flow rate at various points along the specimen are computed by monitoring water content and /or pore water pressure at these points. Details of this method including data analysis are given by Stephens (1994), Olson and Daniel (1981), Fredlund and Rahardjo (1993), Benson and Gribb (997) as well as Hamilton el al. (1981).

The indirect measurement method of determining unsaturated hydraulic conductivity involves determining the water content of the soil specimen at various matric suction values, and then it is calculated with the aid of the various models. The test time for this method is greatly reduced when compared to the direct measurement method since the test only last up to the time the water content in the soil specimen equilibrates with imposed matric suction.

2.21 Soil water characteristics

The relationship between pore water suction and water content, as presented in a Soil Water Characteristics Curve (SWCC) is one fundamental relationship used to describe unsaturated behaviour of a soil (Barbour, 1998). The SWCC describes the relationship between the pore water suction (matric suction, ψ) and water content (gravimetric water content, w) or volumetric water content, θ, or degree of saturation, S_r. The soil water characteristic can be described as a measure of the soil holding capacity (that is, storage capacity) of the soil as the water content changes when subjected to various values of suction.

The soil water characteristic is a conceptual and interpretative tool through which the behaviour of unsaturated soils can be understood. As the soil moves from the saturated state to drier states (unsaturated states), the distribution of the soil, water and air phases change as the stress state changes. The relationships between these phases take on different forms and influence the engineering properties of unsaturated soils (Vanapalli et al, 1999). The engineering behavior of unsaturated soil such as flow, strength and volume change behavior can be understood and predicted (Puppala et al, 2006).

Increasing suction in compacted clays due to decrease in water content modifies the flow behavior of covers. During desiccation, the saturation of a liner is reduced and the remaining pore water is held at increasingly large suction. The relationship between saturation and suction during desiccation is described using SWCCs. Knowledge of suction and corresponding water content in the soil can be used to predict cracking potentials of liners. The onset and resulting amount of cracking can be correlated to a soil-specific critical suction level (Miller et al., 1998). Hence, the SWCC provides critical input to the design of a compacted clay cover liner due to its potential impact on flow rate and the desiccation process.

A typical SWCC that describes the relationship between water content and pore water suction for black cotton clay soil compacted at British Standard Light compactive effort is presented in Figure 2.4. Several defining parameters of the curve include the air entry suction (ψa,) that corresponds to matric suction required to remove water from the largest pores (Brooks and Corey, 1964). The water content corresponding to the asymptote of the SWCC at low degree saturation is called the residual water content (θ_r). It is also the degree of saturation, or gravimetric water content, or volumetric water content beyond which it becomes increasingly difficult to remove water from specimen drainage.

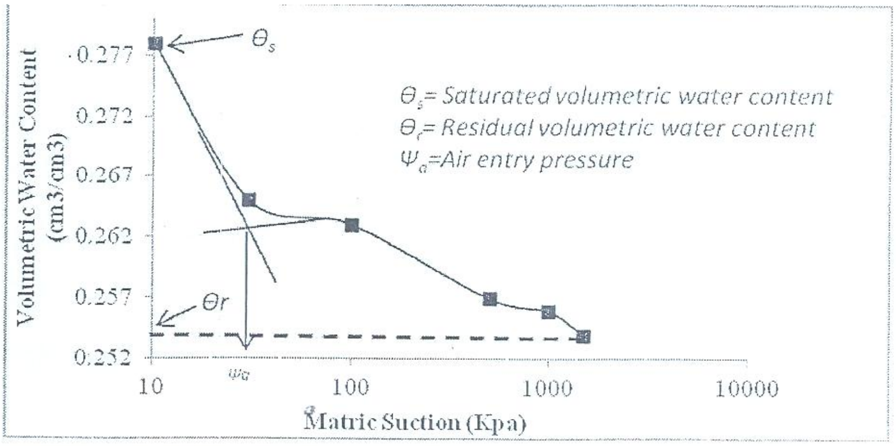


Figure 2.5: Typical soil water characteristic curve of black cotton clay soil compacted at optimum moisture content using British standard light compactive effort. (Adebisi Ramota, 2007)

From the figure, 2.4 the ordinate represents the volumetric water content or gravimetric water content or degree of saturation while the abscissa represents the matric Suction in kilopascal. Various parameters which can be defined from the curve are:

(i). Residual Water Content ($\theta_{r,}$): This is the volumetric water content above which the removal of water from soil sample becomes extremely difficult or at which large suction is required to remove water from the soil.

(ii) Air Entry Suction or Bubbling Pressure (ψ_a): According to Brooks and Corey (1966) this is the matric suction at which water can be removed from the largest pores of the soil sample or at which air can enter the largest pore of the soil (Fredlund and Xing, 1994).

(iii,) Saturated Volumetric Water Content (θ_s): volumetric water content, the maximum amount of water a soil can, Traditionally, SWCC has been defined over a range of suction that is from 0 10 1 500 kPa. A suction value of 1500 kPa has been taken on significance as 'residual suction' because it corresponds to the wilting point for many plants (van Genuchten, 1980). However, this arbitrary value may not likely correspond to the residual state of saturation condition (Vanapalli et al., 1999). At zero water content the soil maine suction is approximately 1000,000 kPa (Croney and Coleman, 1961; Fredlund et. al., 1994). This dry condition is achievable by oven drying the soil, it is necessary to define the residual state of saturation condition in order to obtain the fitting parameter in numerical models for predicting unsaturated hydraulic conductivity (Brooks and Corey, 1964; van Genuchten, 1980).

The shape of the SWCC is a function of the soil type. Soils with smaller pores have higher air entry pressure (ψ_a). Soils with wider ranges of pore sizes exhibit greater changes in matric suction with water content (Hillel, 1980, Fredlund and Rahardjo, 1993). The SWCC of compacted clay soils depend on the compaction water content, compactive effort and plasticity index (Tinjum et al. 1997).

Several models have been used to describe the SWCC, commonly used models include Brooks and Corey (1964), van Genuchten (1980) as well as Fredlund and Xing (1994); and these were reviewed by Leong and Rahardjo (1997a). These three models have been used in this work to describe the unsaturated behaviour of the test soil specimens.

Among the available models for predicting SWCC, the commonly used models are:

(a) Brooks and Corey Model (Brooks and Corey, 1964) which is expressed in Equations The (2.8) and (2.9) respectively.

$$\Theta = \frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} = \left(\frac{\Psi}{\Psi}\right)^{\lambda} \qquad (2.2)$$

$$\theta = 1 \text{ and } \theta = \theta_s \text{ when } \psi \leq \psi_a \qquad (2.9)$$

where: θ = normalized dimensionless volumetric water content.

λ= is the pore-size distribution index (Corey, 994); it is a function of the distribution of pores in the soil sample and can be deduced from the slope of SWCC.

(b) van Genuchten model which is given by Equation (2.2):

$$\Theta = \frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} = \left\{\frac{1}{1 + (\alpha\Psi)^n}\right\}^m \qquad (2.3)$$

(c) Fredlund and Xing (1994) model given by Equation (2.3):

$$\Theta = \frac{\Theta - \Theta_r}{\Theta_s - \Theta_r} = \frac{1}{\left\{\text{in}\left[e + \left(\frac{\Psi}{a}\right)^b\right]\right\}^c} \qquad (2.4)$$

Where a, b, c, m, n and p are three different soil fitting parameters described by Fredlund and Xing (1994) and Leong and Rahardjo (1997a). van Genuchten, (1980) also related m and n as: m $(1 + {}^{1}\!/_{n})$ in order to obtain a closed form expression for hydraulic conductivity but which reduces the flexibility of the model; therefore, the parameters *m* and *n* should be used as obtained without relating them together in order to get accurate predictive results. *P* is the pivot point of the curve, the value of which is related to the air-entry suction. n occurs at normalized volumetric water content of 0.5 and it controls the slope of SWCC about the pivot point such that as *n* increases the portion of the curve between ψ_a and the knee (the point of inflexion) of SWCC becomes steeper (Miller et al.,2002).

According to Vanapalli el al. (1999), several parameters affect the shape of the SWCC for compacted clays; these include plasticity, soil structure, stress state and the type of compaction. Variation in compaction water content and compactive effort also initiate changes in the pore structure of the soil, which results in variation of the shape of the SWCC (Tinjum et al., 1997). In the presence of sufficiently abundant liner fraction, the structure of a soil can be modified by disturbances such as hand kneading and compact Ion (Fernandez-Galvez and Barahona, 2006).

Kneading particularly hand kneading affects soil properties such as geometric mean particle size, and enhances denser packing of particles, with resulting reduction in the total porosity and hence oil water retention capacity of the soil. Other investigations have proven that the SWCC is intimately dependent on soil physical parameters such as grain sizes and texture (Walcaz et al., 2006).

2.22 Volumetric water content

Volumetric water content is a product of gravimetric water content and bulk density of the soil sample. $\theta = \theta_g \text{ x } \gamma_b$

Where θ = normalized dimensionless volumetric water content

θ_g = gravimetric water content

γ_b = bulk density

2.23 Prediction of unsaturated hydraulic conductivity

The unsaturated hydraulic conductivity is usually predicted from the models which relate the saturated hydraulic conductivity with the various parameters obtained from SWCC. This is because it is fundamentally difficult to determine the unsaturated hydraulic conductivity of soil, because it is time dependent, time consuming and variant. The prediction is based on the following relation as Equation (2.12a) (Richards, (1931) and contained in Desad et al., (1992)

$$\frac{\partial \theta}{\partial t} - \nabla . k \nabla kpw - \frac{\partial k}{\partial z} = 0 \qquad (2.5a)$$

Where K = Unsaturated hydraulic conductivity, which is expressed as a relative permeability K_r, P Pressure head, θ = Moisture content of wetting phase, expressed in term of Saturation. S = θ/n and is the porosity, w is wetting phase)

$$K_r = {}^{K}\!/\!{}_{K_{sat}} \tag{2.5b}$$

Where K_r is a relative hydraulic conductivity; K is unsaturated hydraulic conductivity of the soil and is a function, ψ, while K_{sat} is saturated hydraulic conductivity of the soil as calculated from permeability test.

Based on Brooks-Corey model (Brooks and Corey, 1964), relative hydraulic conductivity in relation to SWCC parameters is given by Equation (2.6):

$$K_r = \left\{ 1 \left(\frac{\psi_a}{\psi} \right)^{2+2\lambda} ;\psi \le \psi_a ; \psi_a \ge \psi \right. \tag{2.6}$$

Based on van Genucheten model (van Genuchten, 1980), relative hydraulic conductivity in relation to SWCC fitting parameters is expressed by equation (2.7):

$$= \frac{\left\{ 1 - (\alpha\psi)^{n-1} \left(\left[1 + (\partial\psi)^n \right]^{-m} \right\}^2}{\left[1 + (p\psi^n) \right]^{m/2}} \tag{2.7}$$

m, *n* and *p* are as described in SWCC

Also, the model attributed to Leong and Rahardjo (1997a), contained in Gui e/ al. (2011) has the expression in Equation (2.8) below in relation to SWCC fitting parameters for determining the relative hydraulic conductivity:

$$K_r = \frac{1}{\left\{ in \left[e + \left(\frac{\psi}{a} \right)^b \right] \right\}^c} \tag{2.8}$$

CHAPTER THREE

3.0 MATERIALS AND METHODOLOGY

3.1 Reddish brown soil

The soil samples that were used in this research work are reddish brown lateritic soil that was obtained from University of Benin Campus, Edo State, South-South, Nigeria using the method of disturbed sampling. Lateritic soils in Benin area are often found in the area of peneplain (primary) laterite and are developed in-situ from different parent materials with or without the introduction of externally derived iron. The method of disturbed sampling was employed in obtaining soil samples for laboratory testing. The soil samples were designated as BE (Back of Education), FE (Faculty of Environmental) and BS (Basement) located at Longitude 5 37’ 15” and Latitude 6 24’ 3”, Longitude 5 37’ 11” and Latitude 6 24’ 12”, Longitude 5 36’ 53” and Latitude 6 23’ 49” respectively were obtained at depths of 0.50 – 3.0m. The soils were classified according to the Association of American States Highway and Transportation Officials Classification System (AASHTO, 1986) also according to the Unified Soil Classification System (BS, 1990). Full laboratory investigation has been carried out on soil samples, these include; liquid limits, plastic limit, plasticity index, liquidity index, specific gravity, particle size analysis and specific gravities of the soils are in the range 2.62-2.66, while their pH was in the range 6.10 - 6.20. The percent passing BS No. 200 sieve are in the range 59.2 - 66.4%. The summary of the index properties of the soil samples are summarized in Table 3.0. The results of the particle size distribution are shown on Fig.3.0. The plasticity indexes and activity were generally in the ranges 13 - 16% and 0.70 - 0.75, respectively. These values of activity, A (plasticity index, PI/clay fraction) are typical of those reported for kaolinitic soils by Mitchell (1976), Holtz and Kovacs (1981) as well as Oweis and Khera (1998).

3.2 Sampling

Hand auger was used to collect samples from the respective locations (Faculty of Education, Faculty of Environmental Sciences and Basement). Disturbed samples were collected at various depths of 0.5m to 2.5m and labeled accordingly for proper laboratory analysis.

The following plates shows the process of collection of samp3les from the respective locations.

Plate 3.1: Using hand auger to collect samples from Faculty of Education

Plate 3.2: Taking samples from Faculty of Environmental Sciences

3.3 Preparation and Testing of Specimens

Soil water characteristics curve (SWCC) specimens were prepared with one compactive effort (BSL) to relative OMC. 2.5kg of each specimen was moistened with tap water, mixed thoroughly and compacted in BS moulds and later cored into stainless steel rings with inside diameters of 50mm and heights of 50mm with the aid of a mallet. Each of the 15 specimens was covered with caps at both ends before saturation. The samples were subjected to full saturation by capillary action for a period of 3 weeks.

3.4 Volumetric Pressure Plate Extractor

The SWCC is measured in the laboratory using volumetric pressure plate extractor. Pressure plate extractors work on the principle of axis translation which employs matric suction (pressure difference across the air-water interfaces, $\psi = U_a - U_w$
where U_a is the pore air pressure and U_w is the pore water pressure). In the pressure plate extractor, U_w is maintained constant ($U_w = 0$) and U_a is increased to obtain the desired matric suction (Tinjum et al.; 1997; Wang and Benson, 2004).

A pressure plate extractor consists of two main components: a porous plate air-entry pressure higher than the maximum matric suction to be applied during the test and a sealed pressure cell (Fredlund and Rahardjo, 1993). The porous plate is made of either ceramic or polymeric membranes. In the drying test, the soil starts at a saturated condition and the matric suction is gradually increased leading to a reduction in the water content in the soil specimen. The air-entry ceramic disk and the soil are first saturated. After saturation, excess water is removed from the cell. The soil specimen is placed on the high air-entry ceramic disk inside the retaining cylinder. The cell cover is then mounted and tightened into place and air-pressure is applied to the soil specimen in series of increments to achieve different matric suction (ψ). Each increment in air pressure cause water to be expelled from the specimen until an equilibrium state is reached for the ψ that has been established. Additional increments in outflow are applied only and increment is measured (gravimetrically or volumetrically) to define the water content corresponding to each suction (Benson and Gibb, 1997; Kasim et. al., 1999; Miller et al., 2002; Wang and Benson, 2004).

3.5 Application of Pressure

Pressure was applied in one batche as the pressure plate equipment has capacity for only 16 specimens and for proper observation. The entire pressure application lasted about 3 weeks, while the entire process from specimen preparation, saturation and pressure application lasted about 3 months. Pressure was applied using regulated compressed air from a compressor. The soils were subjected to pressures of 10, 30, 100, 500, 1000 and 1500 kPa, respectively. On completion of the test, the equipment will be disassembled, the soil specimen was removed and replaced in an oven to determine its final gravimetric water content. All computations were made based on the original as-compacted soil volumes.

3.6. Soil water characteristics curve (Soil suction measurements)

3.6.1 Pressure plate drying test

The pressure plate drying test used in this study was conducted to determine the relationships between volumetric water content and matric suction potentials in a soil subjected to pressures ranging between 0 - 1500kPa. A photograph of setup is shown in Plate 3.4. Procedures followed were in accordance with ASTM D3152-72 (ASTM, 1994). The saturated soil specimens were placed in the pressure plate cell (see Plate 3.5) and pressure was applied to a predetermined value to induce matric suction. Testing was terminated when the outflow stopped indicating that specimens had equilibrated with the applied matric suction. The specimens were removed and their volumetric water content was determined. The procedure was repeated to develop an entire SWCC by subjecting the soil specimens to different pressures (0.1 – 1500kPa). The whole process involving specimen preparation, saturation and pressure application took about 3 months to be completed

The researcher right at the front of
Civil Engineering Laboratory,
Ahmadu Bello University Zaria.

The Researcher and the Head of Soil
Science Laboratory Department of Soil
Science, ABU, ZARIA. plate. 3.4

Plate 3.5: Soil specimens prepared to be transferred to the pressure plate cell

Plate 3.6: Soil specimens in the pressure plate cell

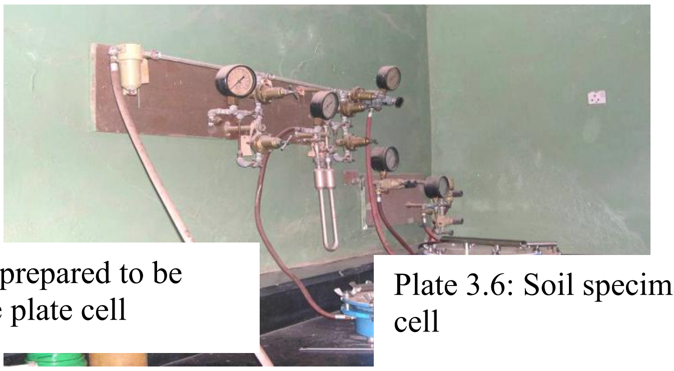


Plate 3.7: Pressure plate extractor setup in the laboratory

3.7 Methods

Various soil tests such as specific gravity, the particle size distribution and Atterberg limits were used to characterize the physical properties of the soil sample used. Other geotechnical tests such as compaction, and unconfined compressive strength (UCS) were also performed. The geotechnical tests on the natural soils were performed in accordance with the procedures outlined in BS 1377 Part 2 (1990) wand BS 1924 (1990), respectively. Specimens for UCS tests were prepared at the optimum moisture content (OMCs) and maximum dry densities (MDDs).

3.8 Specific Gravity

Specific gravity (SG) is a measure of the density of materials in relation to water. Mineral materials such as soil with a specific gravity less than 2 were categorized as light, while those between 2 and 4.5 as average, and those above 4.5 as heavy (Faure, 1998). Sometimes variation may occur between the specific gravities calculated for the same material mineral as a result of the presence of impurities.

The specific gravity of particles was measured according to Test 6(B) BS 1377, Part 2 (1990) using a 50ml density bottle. Air-dried samples were sieved through BS sieve 2mm (o 10) and 30g of representative samples were obtained by mixing various percentage of cement kiln dust by weight of soil sample with the measured soil samples. Each sample was divided into three samples of approximately 10g each which were placed into different 50m1 density bottle of known masses and the masses were recorded. It was then filled with tap water up to three quarter of its volume and left to soak for about ten (10) minutes and thereafter shaken, briskly so as to remove all the entrapped air bubbles from the water-clay solution. It was filled with tap water to the marked level and the mass was recorded. The density bottle was emptied of its content, cleaned and then filled to the marked level with tap water only. The exterior surface of the density bottle was cleaned with a clean, dry cloth and the mass was recorded.

The specific gravity of the solid particles was calculated using the Equation (3.1):

$$\text{specific Gravity (SG)} \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \tag{3.1}$$

where,

M_1 = Mass of the empty density bottle (g)

M_2 = Mass of the empty density bottle filled with air - dry soil only (g)

M_3 = Mass of the empty density bottle filled with soil and water (g)

M_4 = Mass of the empty density bottle filled with tap water only (g)

The average of the three measured values was then determined as the specific gravity of the sample under consideration.

3.9 Atterberg Limits

Atterberg limits test comprises of liquid limit, plastic limit, .linear and volumetric shrinkages. And after drying to the initial length of the sample in which the length of the mould is taken as the initial length of the sample. Equation (3.4) gives the relation for calculating linear shrinkage of the sample. This procedure was repeated for all the samples used.

$$L_s = \frac{L_1 - L_1}{L_1}$$

3.`10 Particle Size Distribution

This test was carried out to determine the various sizes of soil particles in a given sample of soil and also the percentage of the total weight represented by various ranges of grain sizes. BS 1377 (1990) divided particles into groups as follows:

(i)	Gravel particles	-	over 2mm
(ii)	Sand particles	-	between 2 and 0.06mm
(iii)	Silt particles	-	between 0.06 and 0.002mm

The objectives of this test was to determine the particle size distribution of both the natural and the stabilized soil. Sieves analysis is the method for separating a soil into given size fraction.

The particles size distribution of the natural soil and treated soil was determined using both sedimentation analysis and dry sieving of the coarse fraction as specified by BS 1377 (1990) for cohesive soils. The soil sample was washed through BS sieve No. 200 and the materials retained was oven dried and sieved by agitating the material through a range of sieves from sieves No. 10 and downwards, while the material was turned into a sedimentation cylinder for hydrometer analysis for the natural and treated soils.

3.11 Liquid Limit

Apparatus. Drying Oven, flat glass plate about 10 mm thick, Casagrande apparatus, grooving tool, palette knives, wash bottle, BS No. 40 sieve with 425 ui aperture, Moisture content cans.

3.11.1 Procedure: The soil which had been passed through a 425 ni aperture sieve in accordance with Test 1(A) BS 1377, Part 2 (1990) was transferred to the glass plate and water was added till it formed a thick homogenous paste which was kept in an air tight container for 24 hours. A sample of about 200 g from the soil paste was mixed for about 10mins using the two palette knives so that the first blow count was between 40- 50 blows. A portion of the mixed soil was placed in the cup of Casagrande apparatus without entrapping air and the face o fthe soil was leveled. The grooving tool was used to divide the soil into two equal parts by drawing the tool from the hinge towards the front through the centre. The crank handle was turned at a rate of about 2 revolution per second (rev/s) so that the cup was lifted and dropped and the number of blows was counted and recorded. About 10 g of soil was taken with the spatula and placed in moisture content cans for moisture content determination. This was repeated for three more times with the addition of more distilled water.

The moisture content of the soil sample, w, as a percentage of the dry soil mass to the nearest 0.1 % was obtained from equation: (3.2).

$$w = \left(\frac{M_2 - M_3}{M_3 - M_1} \right) x \ 100\% \qquad (3.2)$$

where:

M_1 is the mass of empty container (g)

M_2 is the mass of container and wet soil (g)

M_3 is the mass of container and dry soil (g)

The graph of the varying moisture content against the number of blows was drawn. The moisture content corresponding to 25 blows was obtained from the graph as the liquid limit for the soil sample under investigation.

3.12 Plastic Limit

Plastic limit is used to establish moisture content at which soil passes from liquid state to plastic state. The test was carried out in accordance with Test 1(A) BS 1377, Part 2 (1990) A sample of about 20g was taken from the paste already prepared and was allowed to dry till it became plastic enough to be shaped into a ball. The ball of soil was moulded in between the palms of the hands till the heat of the hands dries the soil sufficiently for slight cracks to appear on it. The soil was then rolled to a thin thread of about 3 mm diameter. The sample was divided into two samples of about 10g each and the moisture content for each determined. The numerical difference between the Liquid Limit and Plastic Limit is referred to as the plasticity index and indicates the degree of the clay content and hence the plasticity of the samples has Calculating using Equation (3.3).

$$P1 = LL — PL \qquad (3.3)$$

3.13 Compaction

The objective of this test is to obtain relationships between dry density and the moisture content of compacted soil. The British Standard Light (BSL) compaction energy were used in this work according to Head (1994a) as well as BS 1924 (1990), and Nigerian General Specifications 11w Roads and Bridges (1997). BSL energy was obtained by using 27 blows of 2.5 kg rammer dropped from 300 mm height on each layer of soil sample placed on 3 layers inside 1000 cm3 mould. On the other hand, WAS is a compactive effort obtained by using 10 blows of 4.5 kg rammer falling from 450 mm height on each layer of soil sample placed in 5 layers inside 1000 cm3 mould,

3.13.1 Procedure: 3 kg sample of air dried soil passing through BS No. 4 sieve with 4.76 mm aperture.

The mould with base plate attached was weighed to the nearest gram. The mould with the attached collar was then placed on a ground and the soil mixture was compacted into the mould in approximately three equal layers, each layer was given 27 blows from 2.5 kg rammer dropped from the height of 30.5 cm above the soil and evenly distributed over surface of each layer. The collar was removed and the compacted soil was carefully levelled using the straight edge and then the mould and the compacted soil are weighed to the nearest gram. A representative sample of the specimen was taken and its moisture content was determined as described earlier. The compacted soil specimen was removed from the mould and remixed in a large metal tray with addition of more water and the procedure was then repeated until the weight of the soil fell. The dry density of the compacted soil sample was then determined from the relation of equation (3.8).

$$\text{Dry Density} = \frac{100 \text{ x Bulk Density} \left({}^{M_g}\!/_{M_3} \right)}{100 \ + \ \text{Moisture Content}} \qquad (3.4)$$

The dry density was afterwards plotted against corresponding moisture contents and maximum dry density and optimum moisture content were determined.

3.14 Unconfined Compressive Strength

The unconfined compressive strength test is one of the methods available for determining shear strength of the soil. It is widely used for research and conventional testing.

3.14.1 Procedure: 3 kg of air-dried soil sample was mixed with optimum moisture content derived from dynamic compaction of the soil sample of the same category. The conventional 13S compaction mould was used. The sample was placed and compacted in the mould in three (3) layers and twenty-seven (27) blows of 2.5 kg rammer were given to each layer. The sample was then removed from the mould with aid of hydraulic jack. Three specimens of 38mm by 76mm were cored out and wrapped in a polythene bag for a minimum of 48 hours to allow for complete saturation. It was then taken to unconfined compression test machine for the test, where axial stress was applied gradually until shear failure occurs. Axial load is applied to the sample. There is constant strain rate. The load is gradually increased to shear the sample, and readings are taken periodically of the force applied to the sample and the resulting deformation. The loading is continued until the soil develops an obvious shearing plane or the deformations become excessive. Failure is taken to have occurred when two or three subsequent readings are equal or reducing.

The experiment was carried out relative to optimum moisture contents following the same procedure and was repeated for BSL compactive efforts. The unconfined compressive strength was computed using Equation (3.5):

$$\text{UCS}\ (\delta) = \text{PCr}\ \frac{(100\ -\ \varepsilon\%) * 10^2}{100\text{A}_o} \qquad 3.5$$

where:

ε = Strain sustained sequent to failure x!Lo

χ = Strain dial reading in mm

L_o = Initial length of tested sample (m)

A^o = Initial cross sectional area of tested sample (rn2)

P = Load Proven Ring reading sequent to failure (kN)

Cr = Compressive Stress Factor

δ = Compressive stress at strain ε (kN/m^2)

3.15 Soil Water Characteristic Curve (SWCC)

3.15.1 Preparation of Samples

All the specimens with respect to soil water characteristic curse (SWCC) used in this test were prepared by compacting relative to the optimum moisture content (OMC), that is, from the dry to the wet side of the line of optimum in the compaction mould for the BSL compactive energy and extruded. Samples were then cored with cylindrical stainless steel rings having inside diameter of 50 mm and height of 50 mm. Eighty-four (84) samples were prepared and sealed at both ends. Before set up, the samples were saturated by placing them in a water immersion tank for about 3 weeks to allow for full saturation which was confirmed when water rose to the surface of the soil samples.

3.15.2 Measurement of SWCC

Volumetric pressure plate extractor was used in the laboratory for the measurement of SWCC. Pressure plate extractors (see plate 3.1) work on the principle of axis translation in which the components of the matric suction (pressure difference across the air-water interfaces as shown in Equation (3.6) are used to obtain the desired matric suction.

$$\mu = \mu_a - \mu_w \tag{3.6}$$

Where μ the pore air pressure and u is, is the pore water pressure. During the test, u was maintained constant (μ_w =0) while μ_a was allowed to increase in order to obtain the desired matric suction (‘Wang and Benson, 2004; Tinjum et al,. 1997). A pressure plate extractor consists of a porous plate and a sealed pressure cell. The porous plate is made of ceramic polymeric membranes and its air-entry pressure is higher than the minimum matric suction applicable during the test (Fredlund and Rahardjo, 1993)

As stated earlier, the compacted soil samples were first saturated and the matric suction is gradually increased which resulted in reduction of the water content in the soil specimen. Similarly, the air-entry ceramic disk was also saturated after which the excess water is removed from the cell. Thereafter the cell cover was mounted and tightened into place and air-pressure was applied to the soil specimen incrementally to achieve different levels of matric suction (μ). Pressure of 10, 30 100, 500, 1000 and 1500 kPa, were applied respectively with the use of regulated air compressor machine and in three batches since the pressure plate could only accommodate 1 6 samples at a time. This increment in air-pressure caused water to be expelled from the specimen until an equilibrium state was achieved for that (μ) attained. Another level of air-pressure was only applied when there was no longer outward expulsion of water from the sample. The amount of the water expelled for each increment of air pressure is measured either volumetrically or gravimetrically and this delineates the water content of the samples for each matric suction applied (Benson and Gribb, 1997; Kasim et al., 1999; Wang and Benson, 2004). At the end of the test, the setup was disassembled; the soil specimens were removed and placed in an oven to determine their final gravimetric water contents. The compacted volumes based on their original dimensions were used for all the computations.

3.16 Laboratory Testing

Residual soil samples used in this study were derived from three locations in the University of Benin, Benin City. The exact locations of the soil were basement, environment, and education. All the disturbed soils were taken at a depth of 0.5m to 2.5m using hand auger.

The index properties of the sample such as particle size distribution and atterberg limit were performed according to BS 1377 at the geotechnical laboratory, faculty of civil and environment engineering, university of Benin.

Five specimen for each location were prepared for the determination of SWCC using pressure plate extractor with capacity of 15000kpa accordance to ASTM 6836-02 (2008) at the geotechnical laboratory, faculty of civil engineering and physics/soil science department of Ahmadu Bello University, Zaria Kaduna State.

The results of the SWCC from basement, environment and education are fitted with Van Genuchten, Brooks-Corey, Fredlund and Xing functions.

Fredlund and Xing (1994) provided an analytical basis for mathematically defining the soil-water characteristic curve. The equation applies over the entire range of suctions from 0 to 1500 kpa. This equation in most commonly written in terms of volumetric water content θ_w, as given below

$$\theta_w = \theta_s \left[1 - \frac{^{\ln}\left(1+\frac{\varphi}{cr}\right)}{\left(1+\frac{10^6}{c_r}\right)} \right] \left[\frac{1}{\mathrm{In}\left[e + \left(\frac{\varphi}{a}\right)^n \right]^m} \right] \qquad 4.1$$

Where

θ_w = volumetric water content
θ^s = saturated volumetric water content
a = suction related to the air-entry value of soil
η = a soil parameter related to the inflection point on the soil water characteristic curve.
φ = soil suction
e = a natural number. 2.71828
C_r = Residual suction

After the completion of the test as stated above the values of the obtained results will be used for the designing of prediction for SWCC, the estimate of the parameters for the Soil Water Characteristic Curve (SWCC) will be carried out using Brooks – Corey (1964), Van Genuchten (1980) and Fredlung – Xing (1994) models

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

Table 4.1 shows the result of the index properties of the soil samples from the three different locations at the University of Benin, Benin-City. It shows specific gravity of all the samples from all the location to be at the range of 2.31-2.57.

The results from the soil samples collected from Basement area shows that the Optimum moisture contents (OMC) ranges between 15.8% - 17.8%, while the maximum dry density (MDD) ranges between 1.58kg/m^3- 1.67kg/m^3, and the maximum bulk density (MBD) ranges from 1.86kg/m^3- 1.94kg/m^3, the sieve analysis shows that the percentage passing through sieve no 0.425mm were all approximately 50% (45.6-51.45)% and percentage passing sieve no 0.075mm where all less than 7% (2.89 – 6.66)%. The liquid limit ranges between 45.18% - 49.61% while the plastic index ranges between 20.38% - 26.82% and this classifies all the soil samples as A-7-2 according ASHTHO and SW-SC according to UCS classification.

The results from the soil samples taken from Faculty of Education shows that the Optimum moisture contents (OMC) ranges between 16.2% - 16.8%, while the maximum dry density (MDD) ranges between 1.64kg/m^3- 1.68kg/m^3, and the maximum bulk density ranges from 1.916kg/m^3- 1.964kg/m^3, the sieve analysis shows that the percentage passing through sieve no 0.425mm were all between the range of 45.6% - 51.45% and percentage passing sieve no 0.075mm were all less than 10% (2.98 – 10.08)%. The liquid limit ranges between 42.04% - 47.13% while the plastic index ranges between 18.61% - 24.64% and this classifies all the soil samples as A-7-2 according ASHTHO classification and according to UCS classification they classification they are classified as SW-SC.

The results of samples taken from Faculty of Environmental Science shows that the Optimum moisture contents (OMC) ranges between 15.0% - 18.2%, while the maximum dry density (MDD) ranges between 1.60kg/m^3- 1.67kg/m^3, and the maximum bulk density ranges from 1.8912kg/m^3- 1.9522kg/m^3, the sieve analysis shows that the percentage passing through sieve no 0.425mm were all between the range of 46.88% - 55.17% and percentage passing sieve no 0.075mm were all less than 7% (3.61 – 6.47)%. The liquid limit ranges between 40.28% - 46.24% while the plastic index ranges between 19.54% - 28.03% and this classifies all the soil samples as A-7-2 according ASHTHO classification and SW-SC according UCS classification The samples were categorized as from low to high plasticity, these shows that all the samples are well graded sand with high clay content this explains the reason for a high value of liquid limit

Table 4.1 Summary of laboratory geotechnical analysis results of all samples used.

	DEPTH	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (Kg/m^3)	MBD (Kg/m^3)	SG	TRIAXIAL		SIEVE		Sample classification	
									C (kN/m^2)	Q (^{o})	0.075 (mm)	0.425 (mm)	ASHTHO	UCS
Basement Area	0.5m	49.11	22.29	26.82	17.8	1.58	1.8612	2.41	28.0	8.47	3.82	50.24	A-7-2	SW-SC
	10m	45.85	25.47	20.38	16.6	1.66	1.9356	2.55	27.0	10.12	5.06	48.62	A-7-2	SW-SC
	1.5m	46.62	23.49	23.13	16.6	1.67	1.9472	2.52	32.0	6.02	3.03	46.11	A-7-2	SW-SC
	2.0m	45.18	21.85	23.33	17.5	1.63	1.9153	2.52	64.0	5.63	6.66	45.6	A-7-2	SW-SC
	2.5m	49.61	22.90	26.71	15.8	1.65	1.9107	2.57	53.0	10.55	2.89	51.45	A-7-2	SW-SC
Faculty of Education														
	0.5m	42.95	25.02	17.92	16.2	1.69	1.9638	2.34	11.0	16.83	5.43	50.81	A-7-2	SW-SC
	1.0m	42.81	24.09	18.92	16.2	1.69	1.9638	2.33	13.0	20.16	2.98	41.83	A-7-2	SW-SC
	1.5m	45.26	23.96	21.30	16.9	1.64	1.9356	2.39	27.0	18.13	3.39	51.36	A-7-2	SW-SC
	2.0m	47.13	22.49	24.64	16.6	1.66	1.9155	2.31	13.0	17.25	10.08	51.9	A-7-2	SW-SC
	2.5m	42.04	23.43	18.61	16.8	1.64	1.9172	2.44	18.0	19.69	3.93	49.85	A-7-2	SW-SC
Faculty of environmental														
	0.5	40.28	20.73	19.54	18.2	1.61	1.903	2.38	24.0	11.75	6.47	46.88	A-7-2	SW-SC
	1.0	46.24	18.20	28.03	17.5	1.65	1.9388	2.43	30.0	17.4	3.86	50.87	A-7-2	SW-SC
	1.5	40.93	20.73	20.20	16.9	1.67	1.9522	2.45	24.0	6.07	4.59	54.63	A-7-2	SW-SC
	2.0	43.18	20.59	22.59	18.2	1.60	1.8912	2.45	39.0	6.84	3.61	55.17	A-7-2	SW-SC
	2.5	46.11	20.59	25.52	15.0	1.66	1.909	2.40	28.0	15.92	3.64	50.33	A-7-2	SW-SC

***Less than 5% passing sieve size 0.075mm = SW (Well graded sand)**

***5% -12% passing sieve size 0.075mm use of dual symbol allowed**

***Atterberg limit above A line and PI greater than 7 = SC (Clayey Sand)**

Table 4.2: Hydraulic Conductivity for the three locations (Basement, education and environment), D_{10} was obtained from Sieve Analysis Test

S/N	LOCATION	DEPTH(M)	C	D_{10}	D_{10}^2	K= $C.D_{10}^2$
	Basement					
1.		0.5	0.01	0.13	0.0169	1.69×10^{-4}
2.		1.0	0.01	0.12	0.0144	1.44×10^{-4}
3.		1.5	0.01	0.15	0.0225	2.25×10^{-4}
4.		2.0	0.01	0.15	0.0225	2.25×10^{-4}
5.		2.5	0.01	0.15	0.0121	1.44×10^{-4}
	Education					
1.		0.5	0.01	0.11	0.0121	1.44×10^{-4}
2.		1.5	0.01	0.12	0.0144	5.63×10^{-4}
3.		2.0	0.01	0.075	0.005625	1.69×10^{-4}
4.		2.5	0.01	0.13	0.0169	2.25×10^{-4}
5.		5.0	0.01	0.15	0.0225	1.69×10^{-4}
	Environment					
1.		0.5	0.01	0.13	0.0169	1.96×10^{-4}
2.		1.0	0.01	0.14	0.0196	1.69×10^{-4}
3.		1.5	0.01	0.13	0.0169	1.96×10^{-4}
4.		2.0	0.01	0.14	0.0196	1.96×10^{-4}
5.		2.5	0.01	0.145	0.021025	2.10×10^{-4}

INDIRECT METHOD: ALLEN HAZEN'S FORMULA OF FINDING PERMEABILITY

K= C $(D_{10})^2$

Where:
K = Permeability
C = Hazen's Constant
D_{10} = soil diameter

Table 4.2 shows the Hydraulic conductivity of each of the soil samples from different location, these values were obtained through the indirect method using Allen Hazen's equation, these values will be used as modeling parameters in the prediction modeling to model for the predicted Hydraulic conductivities for each of the samples at various depth

Table 4.3: Gravimetric water content for samples at the three locations (Faculty of Education, Faculty of Environmental Sciences and Basement)

	Matric Suction (pa)						
EDUCATION		0	0.1	0.3	1	5	15
	0.5	0.169	0.16	0.159	0.15	0.146	0.142
	1.0	0.195	0.183	0.174	0.172	0.17	0.168
	1.5	0.186	0.18	0.178	0.177	0.175	0.173
	2.0	0.186	0.184	0.182	0.181	0.176	0.174
	2.5	0.198	0.184	0.173	0.171	0.168	0.165
ENVIRONMENT		0	0.1	0.3	1	5	15
	0.5	0.195	0.182	0.176	0.173	0.172	0.167
	1.0	0.201	0.185	0.176	0.17	0.168	0.166
	1.5	0.209	0.198	0.189	0.186	0.185	0.183
	2.0	0.203	0.195	0.193	0.186	0.178	0.176
	2.5	0.198	0.185	0.177	0.174	0.17	0.168
BASEMENT		0	0.1	0.3	1	5	15
	0.5	0.175	0.168	0.163	0.159	0.154	0.151
	1.0	0.19	0.18	0.175	0.169	0.156	0.153
	1.5	0.202	0.199	0.186	0.184	0.182	0.179
	2.0	0.191	0.187	0.177	0.174	0.167	0.166
	2.5	0.196	0.187	0.179	0.176	0.172	0.171

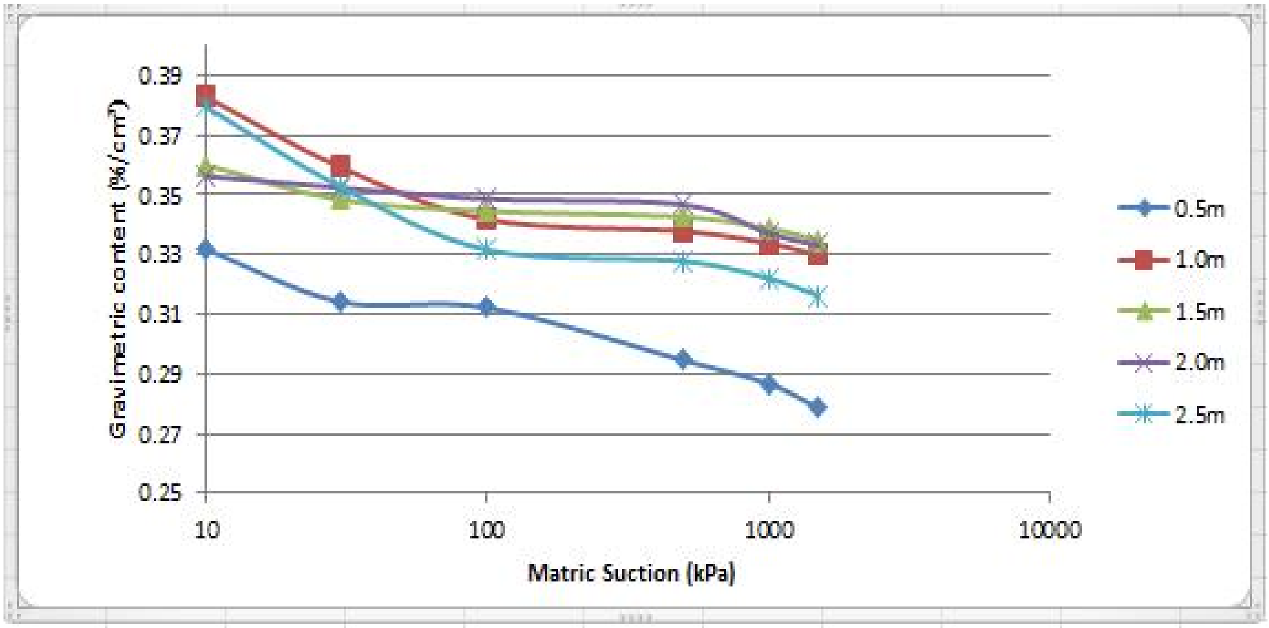


Figure 4.1: Variation of gravimetric water content with matric suction for basement area

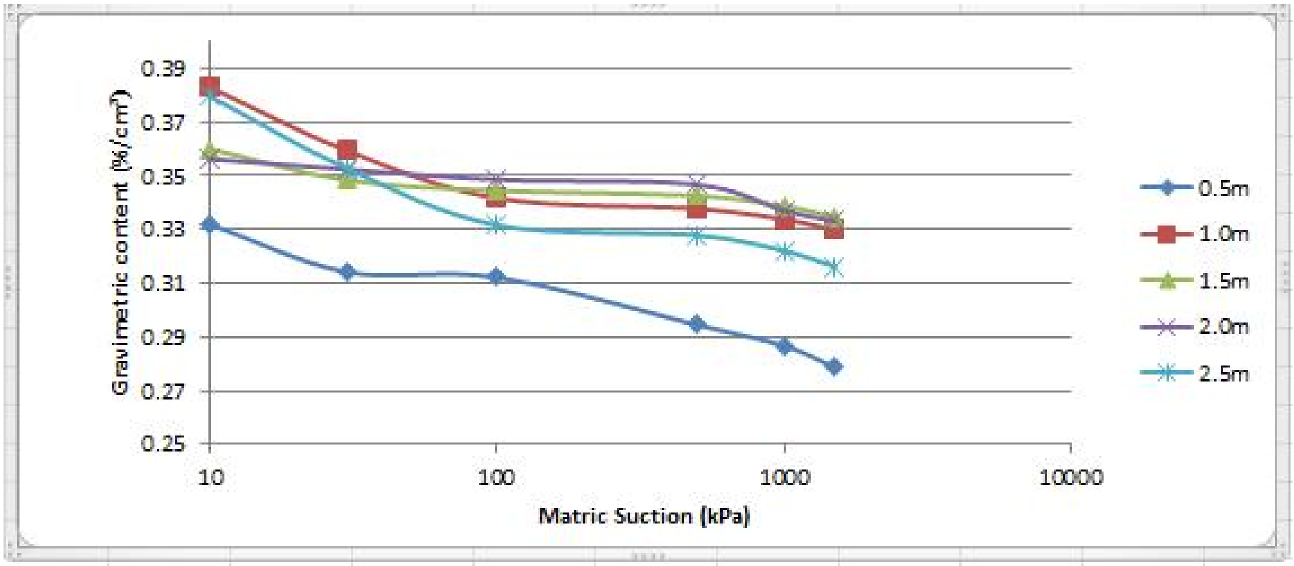


Figure 4.2: Variation of gravimetric water content with matric suction for Faculty of Education Area

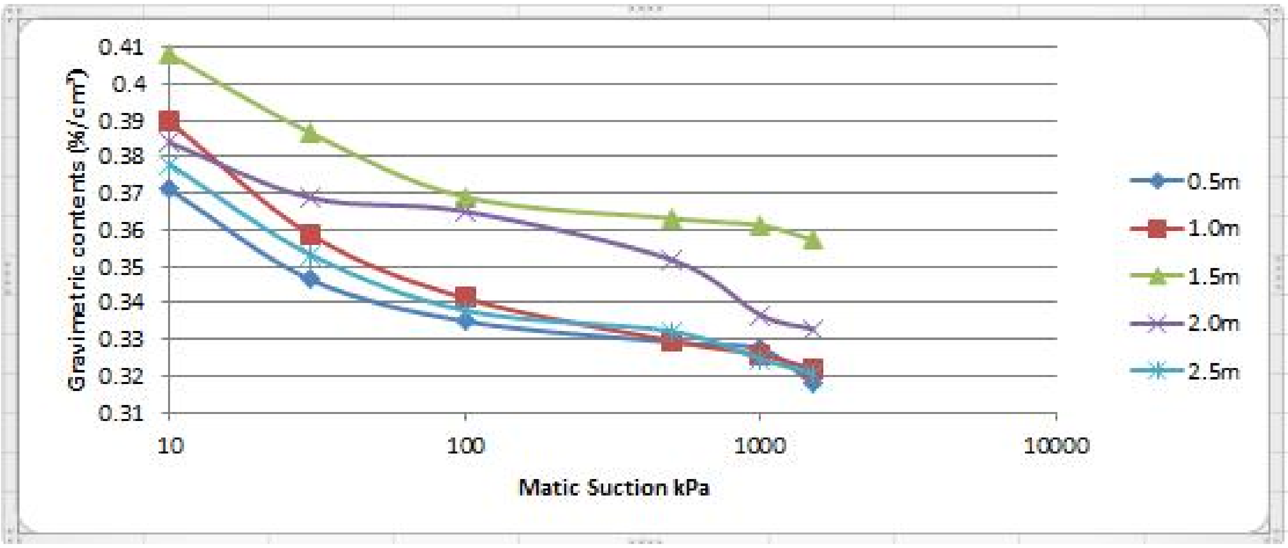
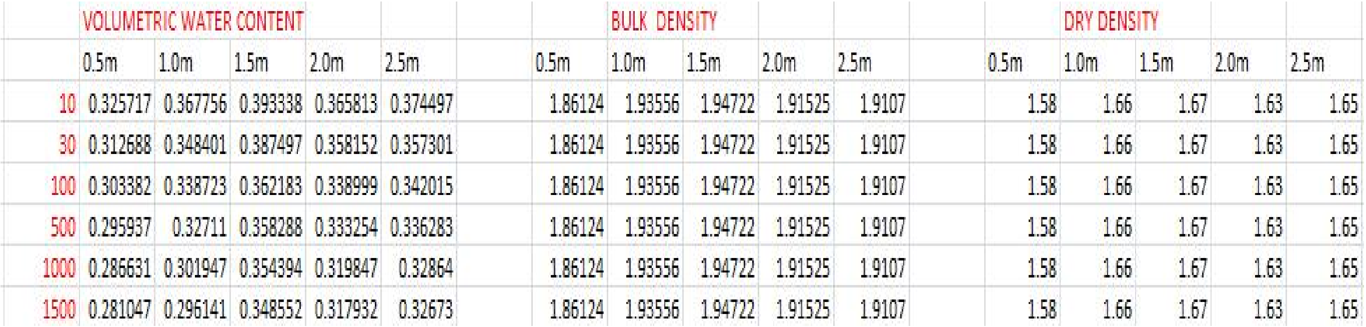


Figure 4.3: Variation of gravimetric water content with matric suction for Faculty of Environmental Sciences Area.

Figure 4.1 to 4.3 shows the relationship between the gravimetric water content and the matric suction of the soil. The graph shows the effect of pressure (matric suction) on the soil gravimetric water content which are expressed on volumetric basis, it shows the water retaining ability of the soil when a certain amount of pressure is applied and also the ability of soil to desiccate water, it can be seen that as the pressure increases (matric suction) there is a reduction in the volumetric water content which shows there is expulsion of water from soil, but the ability to expel or retain water by any soil is largely dependent on the nature and the geotechnical characteristics of the soil

Table 4.4: Volumetric water content for samples at Basement Area



	VOLUMETRIC WATER CONTENT					BULK DENSITY					DRY DENSITY				
	0.5m	1.0m	1.5m	2.0m	2.5m	0.5m	1.0m	1.5m	2.0m	2.5m	0.5m	1.0m	1.5m	2.0m	2.5m
10	0.325717	0.367756	0.393338	0.365813	0.374497	1.86124	1.93556	1.94722	1.91525	1.9107	1.58	1.66	1.67	1.63	1.65
30	0.312688	0.348401	0.387497	0.358152	0.357301	1.86124	1.93556	1.94722	1.91525	1.9107	1.58	1.66	1.67	1.63	1.65
100	0.303382	0.338723	0.362183	0.338999	0.342015	1.86124	1.93556	1.94722	1.91525	1.9107	1.58	1.66	1.67	1.63	1.65
500	0.295937	0.32711	0.358288	0.333254	0.336283	1.86124	1.93556	1.94722	1.91525	1.9107	1.58	1.66	1.67	1.63	1.65
1000	0.286631	0.301947	0.354394	0.319847	0.32864	1.86124	1.93556	1.94722	1.91525	1.9107	1.58	1.66	1.67	1.63	1.65
1500	0.281047	0.296141	0.348552	0.317932	0.32673	1.86124	1.93556	1.94722	1.91525	1.9107	1.58	1.66	1.67	1.63	1.65

SWCC CURVE FROM LABORATORY DATA FOR BASEMENT AREA (See Appendix A for Fitting Parameters obtained)

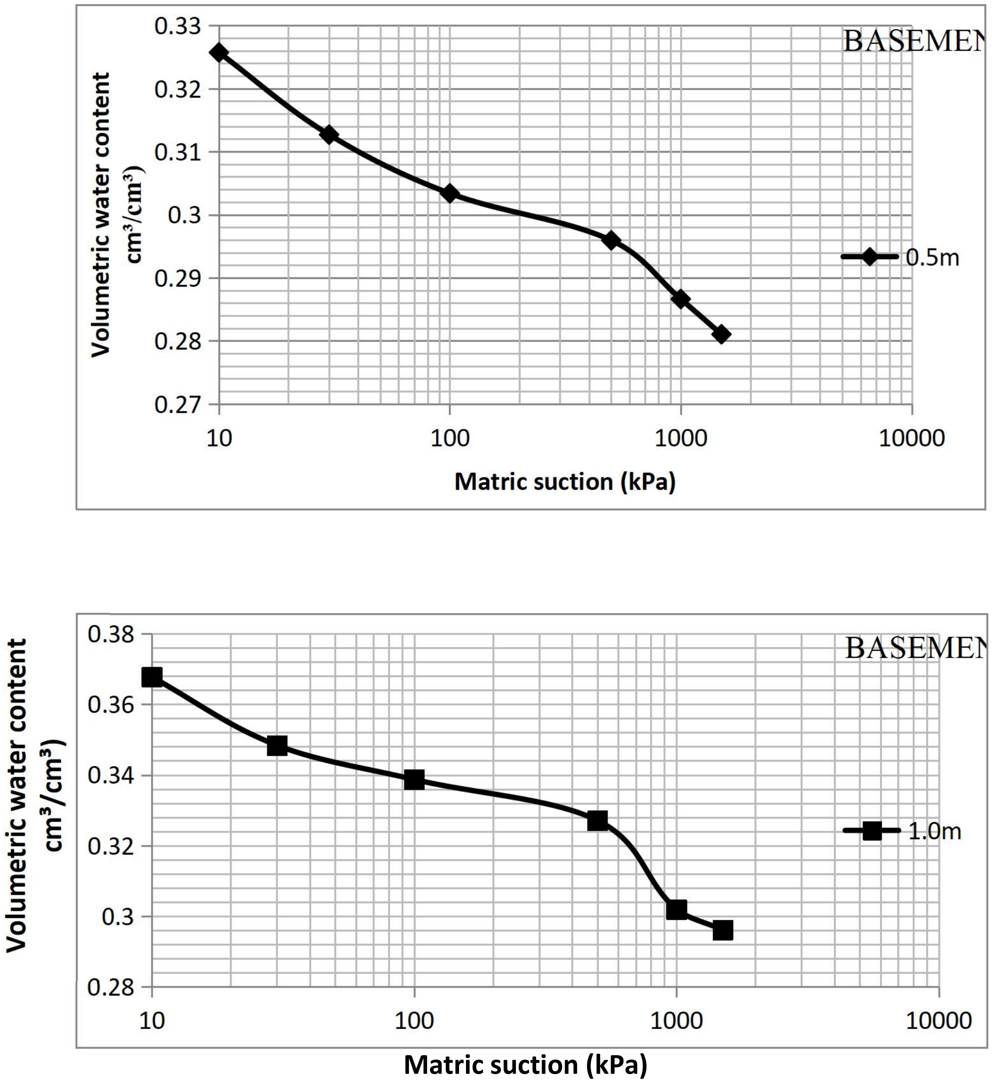


Figure 4.4: Variation of volumetric water content with matric suction for basement area

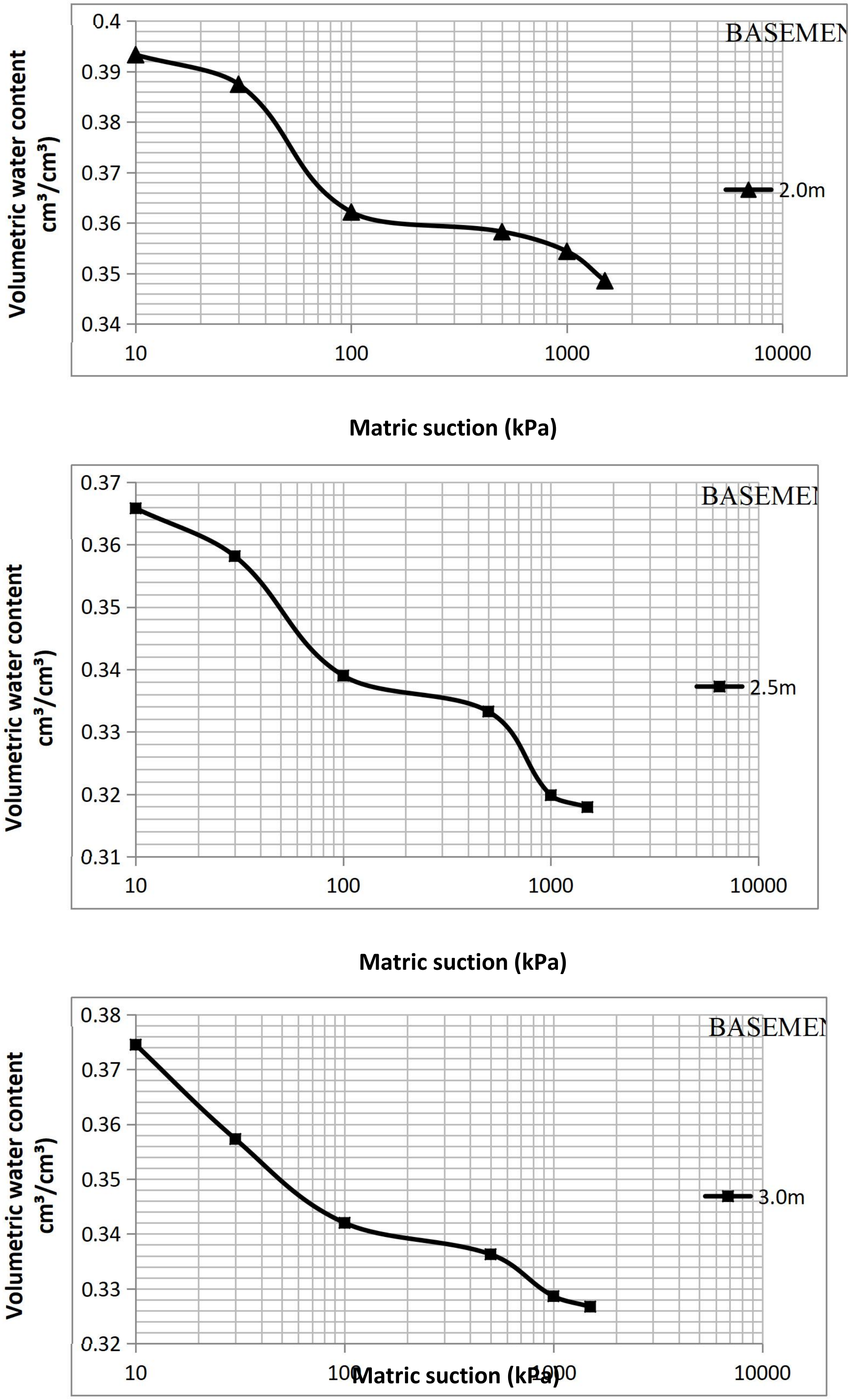
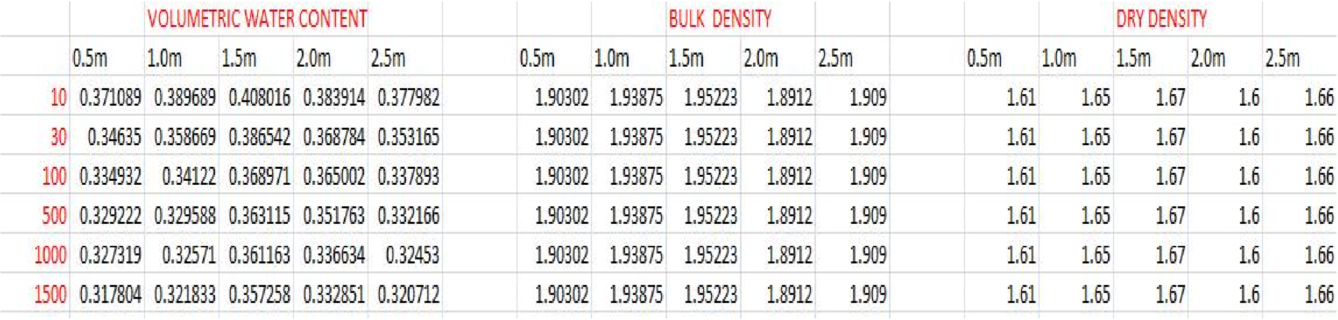


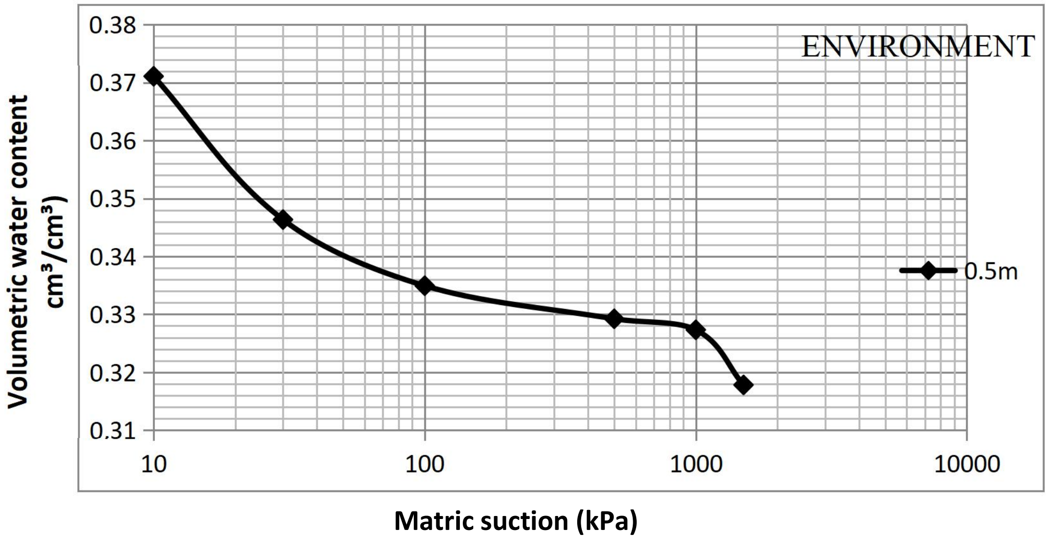
Figure 4.5: Variation of volumetric water content with matric suction for basement area

Table 4.5: Volumetric water content for samples at Faculty of Environmental Sciences Area



	VOLUMETRIC WATER CONTENT					BULK DENSITY					DRY DENSITY				
	0.5m	1.0m	1.5m	2.0m	2.5m	0.5m	1.0m	1.5m	2.0m	2.5m	0.5m	1.0m	1.5m	2.0m	2.5m
10	0.371089	0.389689	0.408016	0.383914	0.377982	1.90302	1.93875	1.95223	1.8912	1.909	1.61	1.65	1.67	1.6	1.66
30	0.34635	0.358669	0.386542	0.368784	0.353165	1.90302	1.93875	1.95223	1.8912	1.909	1.61	1.65	1.67	1.6	1.66
100	0.334932	0.34122	0.368971	0.365002	0.337893	1.90302	1.93875	1.95223	1.8912	1.909	1.61	1.65	1.67	1.6	1.66
500	0.329222	0.329588	0.363115	0.351763	0.332166	1.90302	1.93875	1.95223	1.8912	1.909	1.61	1.65	1.67	1.6	1.66
1000	0.327319	0.32571	0.361163	0.336634	0.32453	1.90302	1.93875	1.95223	1.8912	1.909	1.61	1.65	1.67	1.6	1.66
1500	0.317804	0.321833	0.357258	0.332851	0.320712	1.90302	1.93875	1.95223	1.8912	1.909	1.61	1.65	1.67	1.6	1.66

SWCC CURVE FROM LABORATORY DATA FOR FACULTY OF ENVIRONMENTAL SCIENCES AREA (See Appendix B for Fitting Parameters obtained)



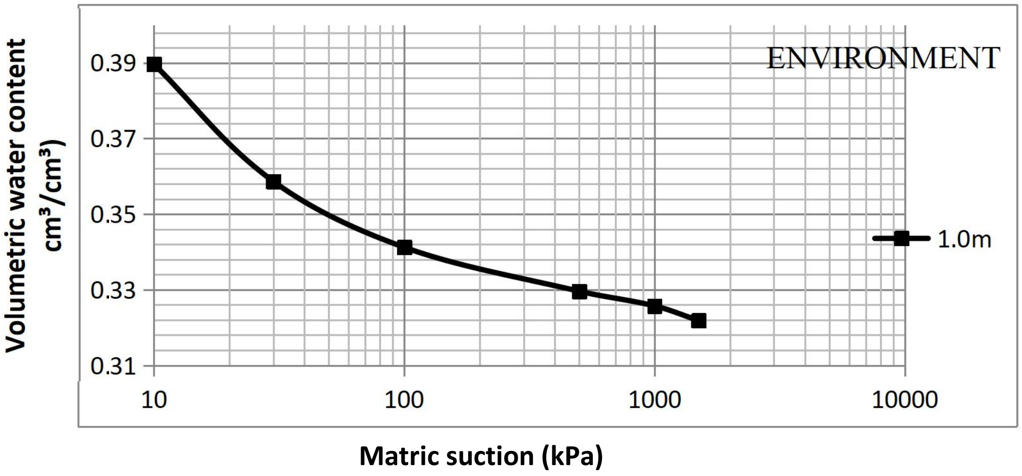


Figure 4.6: Variation of volumetric water content with matric suction for faculty of environmental sciences area

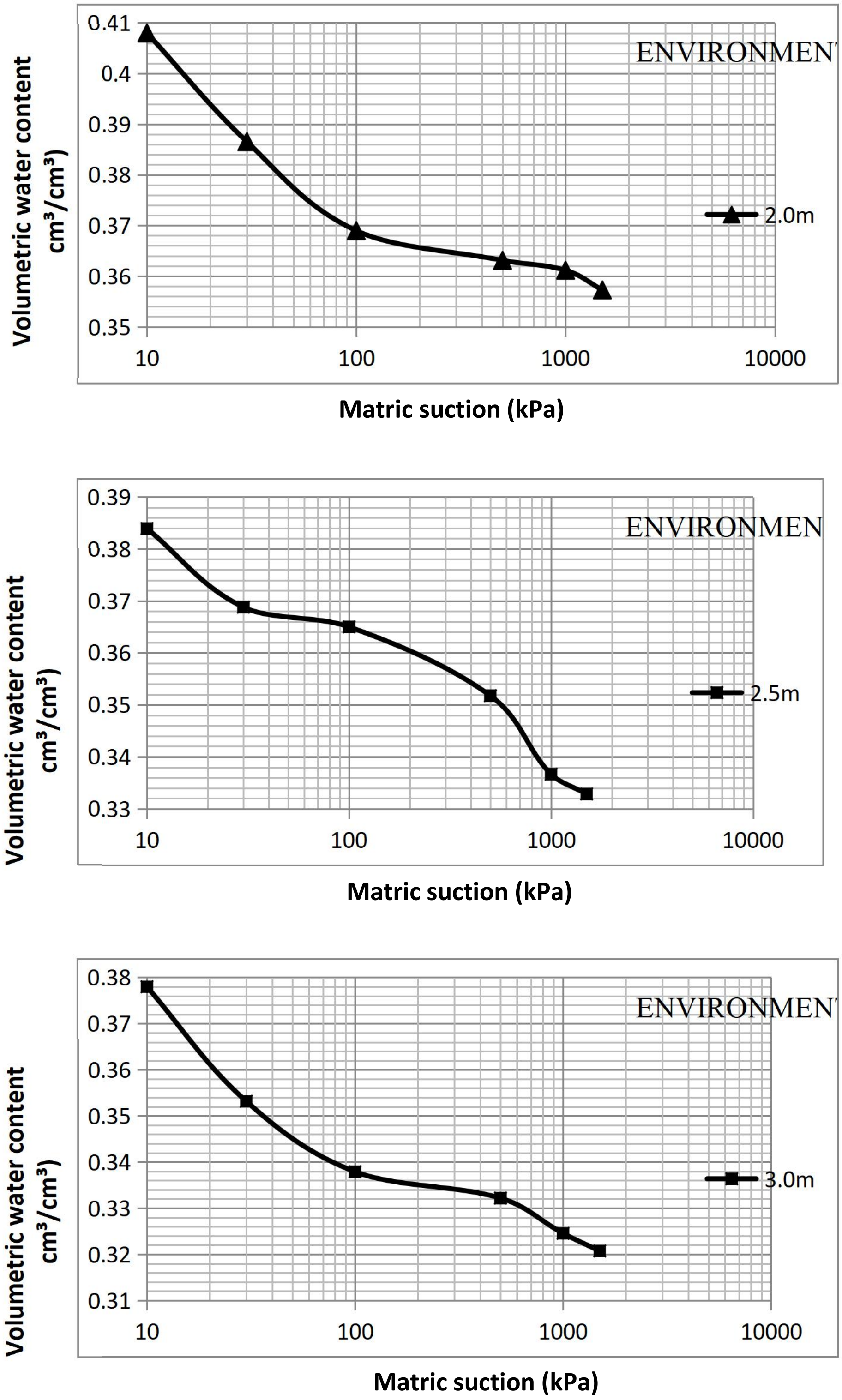


Figure 4.7: Variation of volumetric water content with matric suction for faculty of environmental sciences area

Table 4.6: Volumetric water content for samples at Faculty of Education Area

	VOLUMETRIC WATER CONTENT					BULK DENSITY					DRY DENSITY				
	0.5m	1.0m	1.5m	2.0m	2.5m	0.5m	1.0m	1.5m	2.0m	2.5m	0.5m	1.0m	1.5m	2.0m	2.5m
10	0.331879	0.382937	0.360014	0.356287	0.379598	1.96378	1.96378	1.93556	1.91552	1.91716	1.69	1.69	1.66	1.64	1.64
30	0.314205	0.359372	0.348401	0.352456	0.352757	1.96378	1.96378	1.93556	1.91552	1.91716	1.69	1.69	1.66	1.64	1.64
100	0.312241	0.341698	0.34453	0.348625	0.331669	1.96378	1.96378	1.93556	1.91552	1.91716	1.69	1.69	1.66	1.64	1.64
500	0.294567	0.33777	0.342594	0.346709	0.327834	1.96378	1.96378	1.93556	1.91552	1.91716	1.69	1.69	1.66	1.64	1.64
1000	0.286712	0.333843	0.338723	0.337132	0.322083	1.96378	1.96378	1.93556	1.91552	1.91716	1.69	1.69	1.66	1.64	1.64
1500	0.278857	0.329915	0.334852	0.3333	0.316331	1.96378	1.96378	1.93556	1.91552	1.91716	1.69	1.69	1.66	1.64	1.64

SWCC CURVE FROM LABORATORY DATA FOR FACULTY OF EDUCATION AREA (See Appendix A for Fitting Parameters obtained)

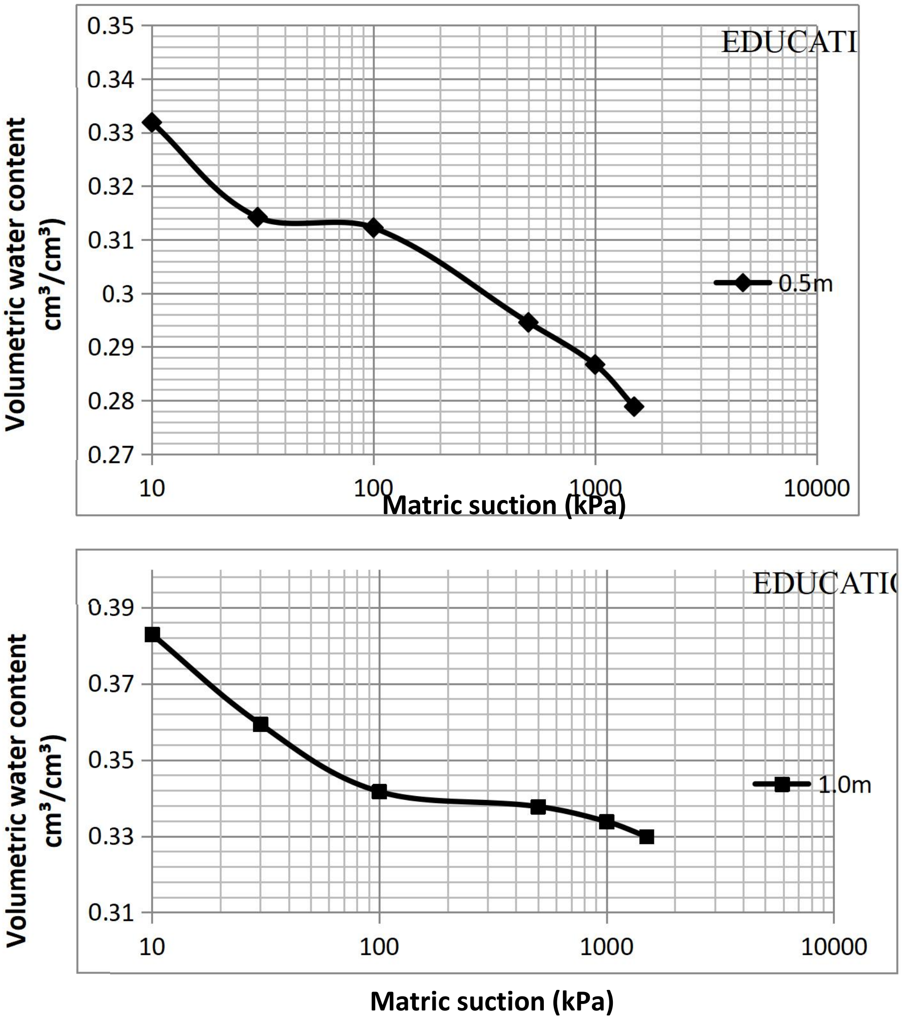


Figure 4.8: Variation of volumetric water content with matric suction for faculty of education area

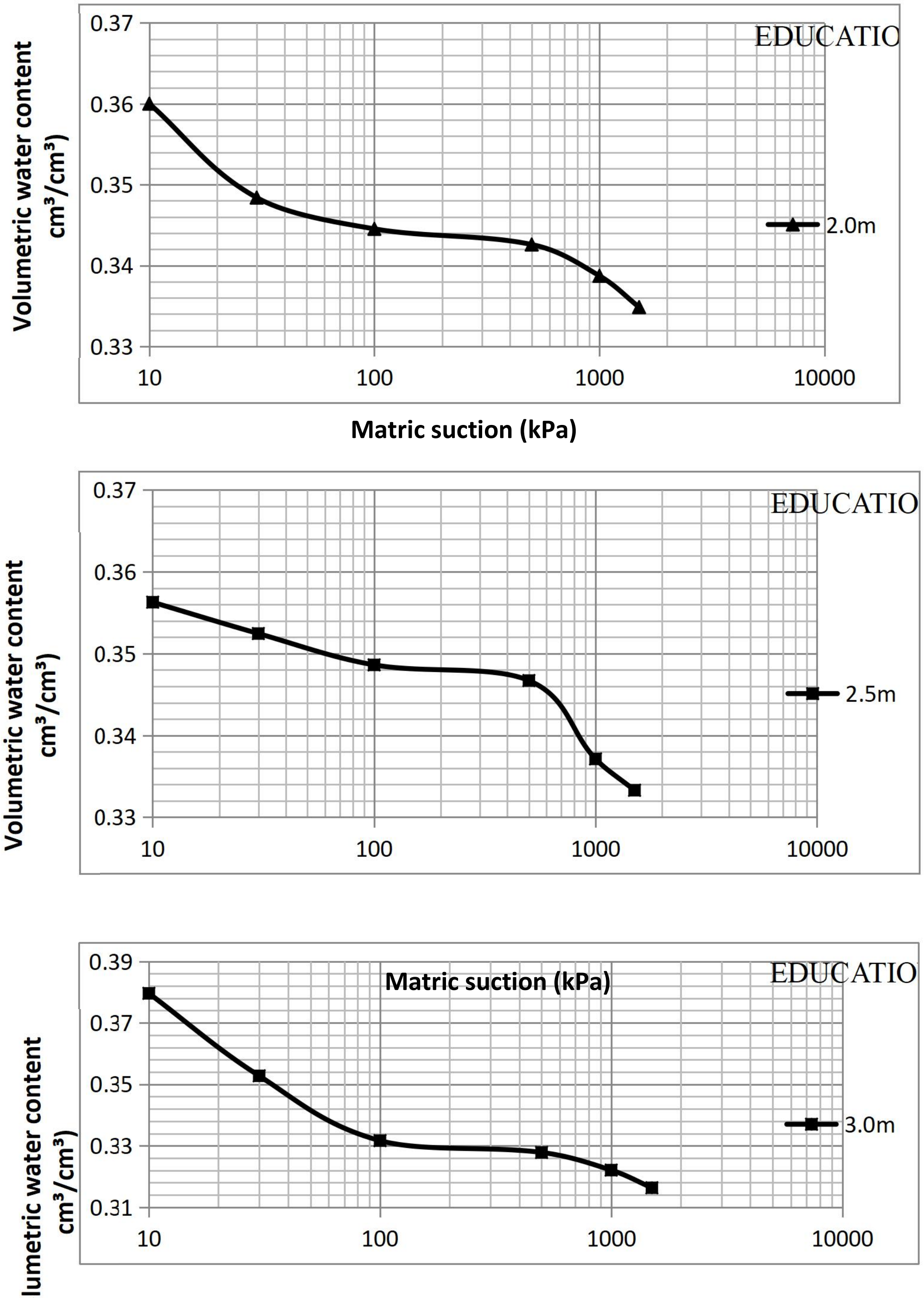


Figure 4.9: Variation of volumetric water content with matric suction for faculty of education area

Figure 4.4 to 4.9 shows the volumetric water content, it expresses the volume of moisture for a given volume of soil, it has a similar pattern of behavior to that of gravimetric water content, but it measures the water content per volume of soil, it is obtained from the product of gravimetric values and bulk density.

SUMMARY TABLE OF BEST FIT PARAMETERS OBTAINED FROM THE PREDICTED SWCC BASED ON LABORATORY EXPERIMENTAL DATA OF THE THREE LOCATIONS (BASEMENT, EDUCATION AND ENVIRONMENTAL)

LOCATION	DEPTH (m)	MATRIC SUCTION (KPA)	AIR ENTRY VALUE (Ω_a)	SATURATED VALUE	RESIDUAL VALUE	SLOPE @ ARBITRARY POINT	SUCTION @ ARBITRARY POINT (Ω_a)	VOLUMETRIC WATER CONTENT @ ARBITRARY POINT (cm^{3}cm^{-3})	Y1	Y2	X1	X2	LOG X1	LOG X2
BASEMENT	0.5	0 – 1500	27	0.3257	0.281047	0.022605	200	0.30	0.296	0.3118	100	500	2	2.6989
	1.0	0 – 1500	26	0.367756	0.296141	0.015421	140	0.336	0.332	0.344	50	300	1.69897	2.47712
	1.5	0 – 1500	30	0.393338	0.348552	0.052151	57	0.373	0.366	0.382	40	80	1.602061	1.90309
	2.0	0 – 1500	29	0.365813	0.317932	0.039863	55	0.347	0.342	0.354	40	80	1.602061	1.90309
	2.5	0 – 1500	24	0.374497	0.32673	0.008773	240	0.3384	0.337	0.341	140	400	2.146128	2.60206
ENVIRONMENT	0.5	0 – 1500	24	0.371089	0.317804	0.008773	230	0.332	0.33	0.334	140	400	2.146128	2.60206
	1.0	0 – 1500	25	0.389689	0.321833	0.015737	220	0.3345	0.33	0.341	100	500	2	2.69897
	1.5	0 – 1500	24	0.408016	0.357258	0.035181	46	0.379	0.372	0.386	30	75	1.477121	1.875061
	2.0	0 – 1500	25	0.383914	0.320712	0.019125	220	0.359	0.354	0.364	120	400	2.079181	2.60206
	2.5	0 – 1500	21	0.377982	0.320712	0.008195	220	0.335	0.333	0.337	130	400	2.113943	2.60206
EDUCATION	0.5	0 – 1500	27	0.331879	0.278837	0.025752	240	0.304	0.294	0.312	100	500	2	2.69897
	1.0	0 – 1500	23	0.382937	0.329915	0.01661	43	0.353	0.348	0.353	30	60	1.477121	1.778151
	1.5	0 – 1500	24	0.360014	0.334852	0.001874	190	0.344	0.3424	0.344	70	500	1.845098	2.69897
	2.0	0 – 1500	30	0.356287	0.3333	0.033632	670	0.3418	0.337	0.346	544	1000	2.732394	3
	2.5	0 – 1500	18	0.379598	0.316331	0.043481	45	0.344	0.336	0.352	30	70	1.477121	1.845098

Figure 4.7: Summary Table of predicted hydraulic productivity results using the 3 Models For 0.5m Depth of all the locations (Basement, Education and Environment).

	BASEMENT AREA			FACULTY OF EDUCATION			FAC. OF ENVIRONMENT SCIENCE		
kpa	Van genutche	Brook-Corey	Fredlund and Xin	Van genutche	Brook-Corey	Fredlund and Xin	Van genutche	Brook-Corey	Fredlund and Xin
10	$1.0x10^{-4}$	$3.76x10^{-3}$	$1.65x10^{-4}$	$7.34x10^{-5}$	1.71	$1.4x10^{-4}$	$5.22x10^{-8}$	$2.53x10^{-3}$	$1.80x10^{-4}$
30	$6.6x10^{-4}$	$1.23x10^{-4}$	$1.58x10^{-4}$	$4.96x10^{-4}$	$6.67x10^{-2}$	$1.31x10^{-4}$	$6.42x10^{-7}$	$1.02x10^{-4}$	$1.79x10^{-4}$
100	$3.0x10^{-3}$	$3.16x10^{-6}$	$1.44x10^{-4}$	$2.06x10^{-3}$	$1.91x10^{-3}$	$1.15x10^{-4}$	$4.55x10^{-7}$	$3.04x10^{-6}$	$1.79x10^{-4}$
500	$1.67x10^{-2}$	$2.38x10^{-8}$	$1.26x10^{-4}$	$1.09x10^{-2}$	$1.65x10^{-5}$	$9.61x10^{-5}$	$1.09x10^{-7}$	$2.76x10^{-8}$	$1.71x10^{-4}$
1000	$3.33x10^{-2}$	$2.90x10^{-9}$	$1.20x10^{-4}$	$2.14x10^{-2}$	$2.13x10^{-6}$	$9.03x10^{-5}$	$5.12x10^{-8}$	$3.65x10^{-9}$	$1.75x10^{-4}$
1500	$4.96x10^{-2}$	$8.45x10^{-10}$	$1.17x10^{-4}$	$3.14x10^{-2}$	$6.44x10^{-7}$	$8.75x10^{-5}$	$3.23x10^{-8}$	$1.12x10^{-9}$	$1.75x10^{-4}$

PREDICTION OF HYDRAULIC CONDUCTIVITY USING (VAN-GENUTCHEN, BROOKS-COREY AND FREDLUND AND XING MODELS) FOR SOIL SAMPLES

From the modeling carried out in this chapter Fredlund and Xing (1994) provided an analytical basis for mathematically defining the soil water characteristic curve (SWCC) of each soil sample. The equation applies over the entire range of suction from 0 – 1,500kpa.

This equation is most commonly written in term of volumetric water content θ_w. Model parameters are defined as follows

θ = Volumetric water content

θ_s = saturated volumetric water content

a = suction related to the air – entry value of the soil

n= a soil parameter related to the slope inflection point on the SWCC

ψ = soil suction

m= a soil parameter related to the residual water content

e= a natural number 2.71828 and

c= residual suction

The best fit parameters for Fredlund and Xing equation are found to describe the soil – water characteristics curve over the entire range of suction.

The values of best fit parameters from the SWCC are substituted back to the model equation (Fredlund and Xing). The fitting parameters a, n and m are then determined. These were later used to predict the hydraulic conductivity (ku) and volumetric water content of the unsaturated soil samples at the three locations (Basement, Environmental and Education).

Brooks-Corey model parameters described the soil hydraulic properties of the soil. The parameters are described where;

θ= volumetric soil-water content (cm^3cm^{-3})

θ_r and θ_s are residual and saturated water content (cm^3cm^{-3})

k_s= saturated hydraulic conductivity (m/s)

n= a constant related to the shape of SWCC

m= (l+1)n+2 where l is the soil pore tortuosity factor, for which l is 2 as being used.

The Van genutchen model parameters are the same as that of Brooks-corey as explained above. From results obtained it has been validated that engineering properties of unsaturated soils such as K (hydraulic conductivity) had been reasonable well predicted using the saturated soil properties and SWCC

Van Genuchten, 1980, proposed the next equation with three fitting parameters:

$$\theta_w = \theta_r = \frac{\theta_s - \theta_r}{\left[1+\left(\frac{h}{a}\right)^b\right]^c} \text{-- - - - - - -}$$

Where:

θ_w = Volumetric water content

θ_r = Residual volumetric water content

a = Soil parameter which is a function of the air entry value of the soil

b = Soil parameter which is a function of the rate of water extraction of the soil after exceeding the air entry value

c = Soil parameter which is a function of the residual water content of the soil

Van Genuchten, equation with three fitting parameters: is expressed in excel format as shown below for easy analysis whereby the best fit parameters from SWCC are inputed into the model to predict the three fitting parameters in the equation above. The predicted fitting parameters were used to predict the hydraulic conductivity and volumetric water content change of the soil testing in the second version of the excel format model at different locations and depths.

Table 4.8: Van genutchen model using SWCC parameters (Basement Area)

			Vangenuchen			
	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATED	0.325717	0.367756	0.393338	0.365813	0.374497
	RESIDUAL	0.281047	0.296141	0.348552	0.317932	0.32673
	ORDINAR	0.022335	0.035808	0.022393	0.023941	0.023884
compaction volumetric waterconten	ϕ	0.303	0.332	0.371	0.342	0.351
	Ωa	27	26	30	29	24
suction at abitrary point P	Ω	200	140	57	55	240
	Y1	0.296	0.332	0.366	0.342	0.337
	Y2	0.3118	0.344	0.382	0.354	0.341
	X1	2	1.69897	1.60206	1.60206	2.146128
	X2	2.69897	2.477121	1.90309	1.90309	2.60206
	SLOPE	0.022605	0.015421	0.053151	0.039863	0.008773
	SP	0.50604	0.215332	1.186772	0.832542	0.183665
	m*	0.33	0.16	0.62	0.49	0.14
parameter	n*	1.50	1.19	2.63	1.95	1.16
	1/m	-3.0038	-6.31933	-1.6129	-2.05652	-7.31809
	0.5power	8.021123	79.85628	3.058667	4.159826	159.5752
	B22-1	7.021123	78.85628	2.058667	3.159826	158.5752
	1/n	0.667089	0.841755	0.38	0.513742	0.863352
	q	3.669681	39.50684	1.315718	1.805918	79.35576
parameter	Alpha*	0.018	0.282	0.023	0.033	0.331
	n-1	0.499051	0.187993	1.631579	0.946501	0.158276
	q pow(n-1)	1.913279	1.996016	1.564672	1.749706	1.998283
	q pow(n)	7.021123	78.85628	2.058667	3.159826	158.5752
	1+b29	8.021123	79.85628	3.058667	4.159826	159.5752
	B30pow-m	0.5	0.5	0.5	0.5	0.5
	b31*b28	0.956639	0.998008	0.782336	0.874853	0.999141
	1-b32	0.043361	0.001992	0.217664	0.125147	0.000859
	b33pow 2	0.00188	3.97E-06	0.047378	0.015662	7.37E-07
	m/2	0.166456	0.079122	0.31	0.243129	0.068324
	b30pom/2	1.414214	1.414214	1.414214	1.414214	1.414214
	Kr	0.001329	2.81E-06	0.033501	0.011075	5.21E-07
	Ks	2.62E-08	4.39E-09	1.34E-09	2.95E-07	5.26E-08
	Ku	3.48E-11	1.23E-14	4.50E-11	3.26E-09	`

Table 4.9: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen Model for 0.5m depth (Basement Area)

PREDICTION SWCC OF UNSATURATED HYDRAULIC CONDUCTIVITY (Ku) FOR VANGENUTCHEN RBSL

	Depth	0.5m					
	pressure	10	30	100	500	1000	1500
	m	0.33	0.33	0.33	0.33	0.33	0.33
	n	1.50	1.50	1.50	1.50	1.50	1.50
	Alpha*	0.018	0.018	0.018	0.018	0.018	0.018
	A=Alpha*ı	3.329111786	9.98733536	33.2911179	166.4555893	332.9111786	499.366768
	A^{n-1}	1.822503498	3.15337842	5.75067896	12.83927883	18.14553914	22.2151041
	A^{n}	6.067317874	31.4938478	191.446531	2137.169723	6040.85282	11093.4847
	$B=1-A^{n-1}$	-0.8225035	-2.1533784	-4.750679	-11.8392788	-17.1455391	-21.2151041
	$C=1+A^{n}$	7.067317874	32.4938478	192.446531	2138.169723	6041.85282	11094.4847
	$D=C^{-m}$	0.964756094	0.93812532	0.90800146	0.868758427	0.852357037	0.84290519
	E=B*D	-7.935E-01	-2.020E+00	-4.314E+00	-1.029E+01	-1.461E+01	-1.788E+01
	E^{2}	0.62966647	4.08096086	18.6073473	105.7909601	213.5725307	319.777415
	$C^{m/2}$	1.018101869	1.03245129	1.04943785	1.072878358	1.083151548	1.08920753
	Kr	0.618470989	3.95269094	17.7307758	98.6048039	197.1769612	293.587223
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Pred. unsat. H.C.	Ku	1.05E-04	6.68E-04	3.00E-03	1.67E-02	3.33E-02	4.96E-02
		***			***		***
	0.5m	10	30	100	500	1000	1500
		1.05E-04	6.68E-04	3.00E-03	1.67E-02	3.33E-02	4.96E-02

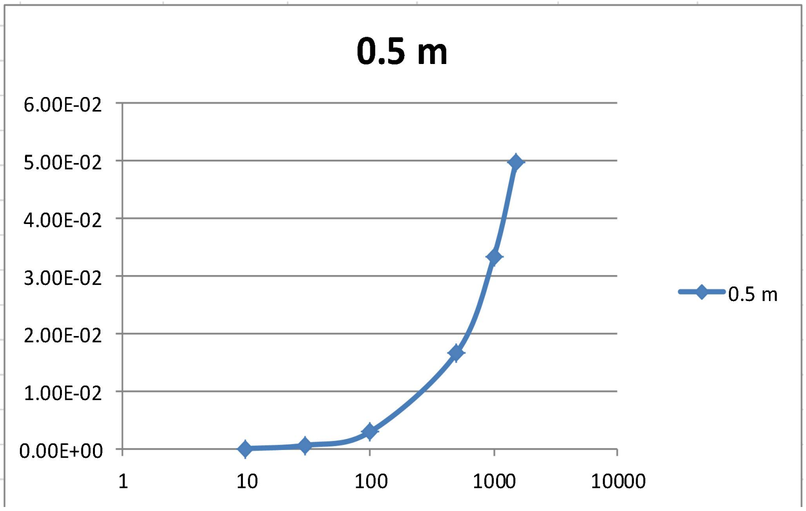
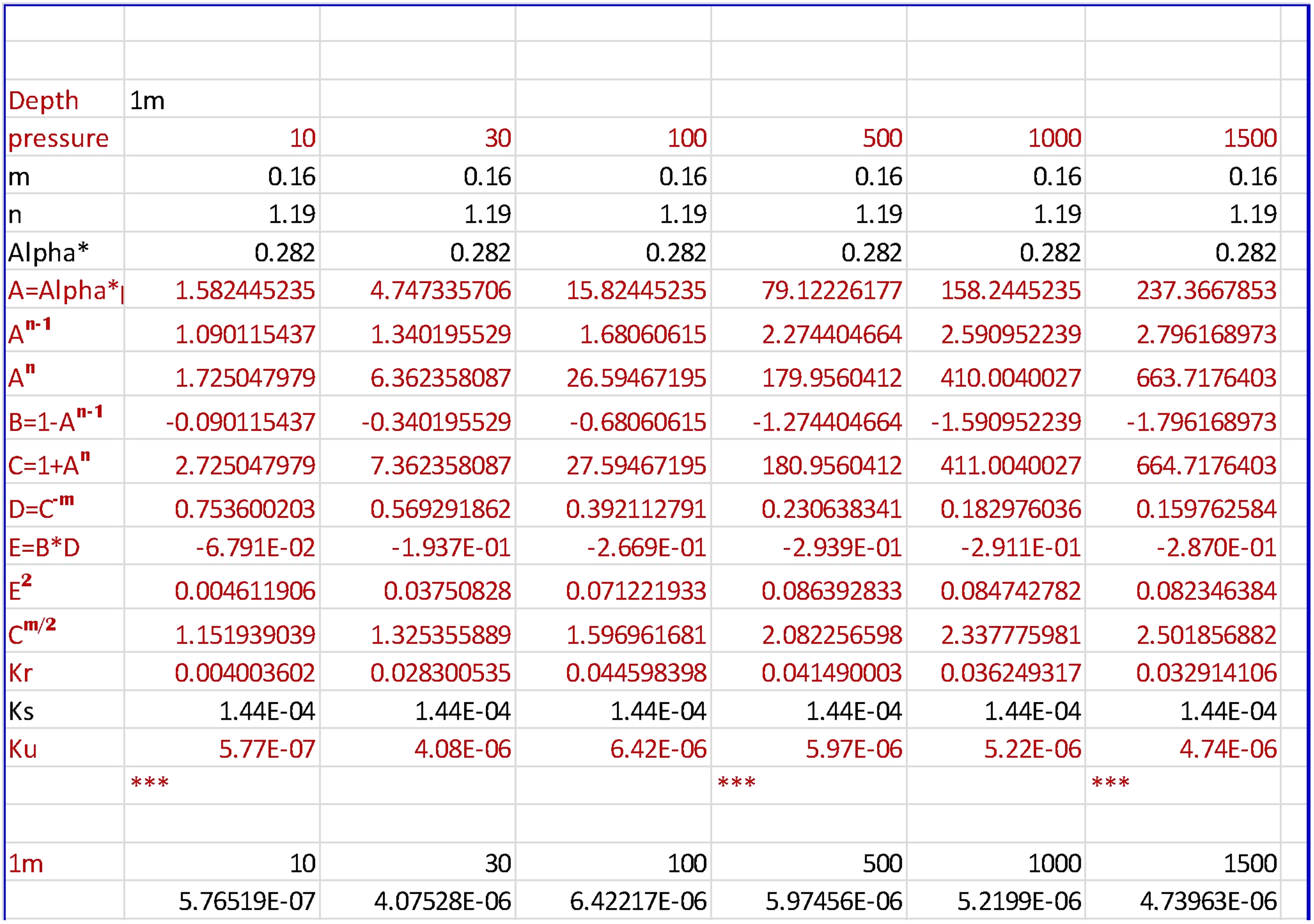


Figure 4.7: Predicted Ku with matric suction

Table 4.10: Prediction of unsaturated hydraulic conductivity (Ku) using Van genutchen Model for 1.0m depth (Basement Area)



Depth	1m					
pressure	10	30	100	500	1000	1500
m	0.16	0.16	0.16	0.16	0.16	0.16
n	1.19	1.19	1.19	1.19	1.19	1.19
Alpha*	0.282	0.282	0.282	0.282	0.282	0.282
A=Alpha*	1.582445235	4.747335706	15.82445235	79.12226177	158.2445235	237.3667853
A^{n-1}	1.090115437	1.340195529	1.68060615	2.274404664	2.590952239	2.796168973
A^{n}	1.725047979	6.362358087	26.59467195	179.9560412	410.0040027	663.7176403
$B=1-A^{n-1}$	-0.090115437	-0.340195529	-0.68060615	-1.274404664	-1.590952239	-1.796168973
$C=1+A^{n}$	2.725047979	7.362358087	27.59467195	180.9560412	411.0040027	664.7176403
$D=C^{-m}$	0.753600203	0.569291862	0.392112791	0.230638341	0.182976036	0.159762584
E=B*D	-6.791E-02	-1.937E-01	-2.669E-01	-2.939E-01	-2.911E-01	-2.870E-01
E^{2}	0.004611906	0.03750828	0.071221933	0.086392833	0.084742782	0.082346384
$C^{m/2}$	1.151939039	1.325355889	1.596961681	2.082256598	2.337775981	2.501856882
Kr	0.004003602	0.028300535	0.044598398	0.041490003	0.036249317	0.032914106
Ks	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
Ku	5.77E-07	4.08E-06	6.42E-06	5.97E-06	5.22E-06	4.74E-06
	***			***		***
1m	10	30	100	500	1000	1500
	5.76519E-07	4.07528E-06	6.42217E-06	5.97456E-06	5.2199E-06	4.73963E-06

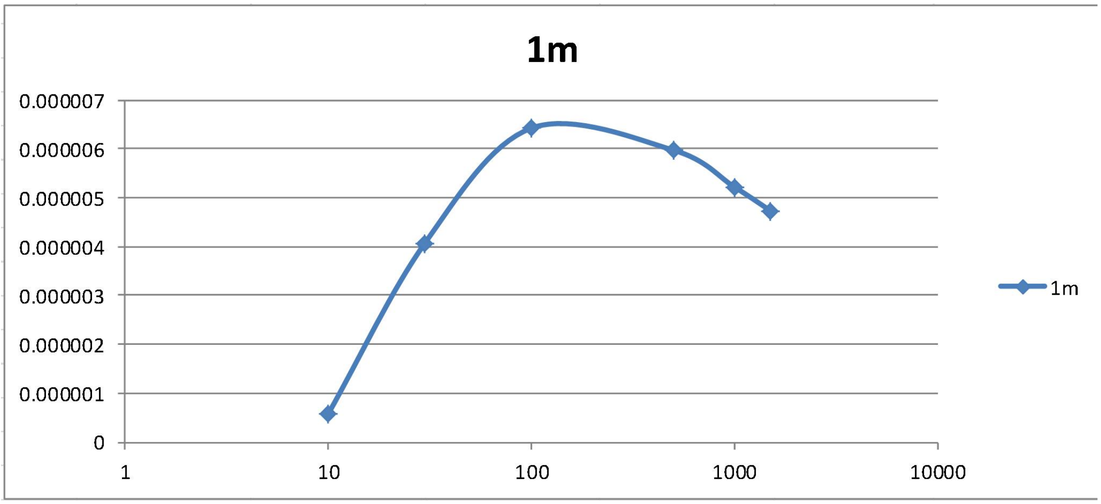
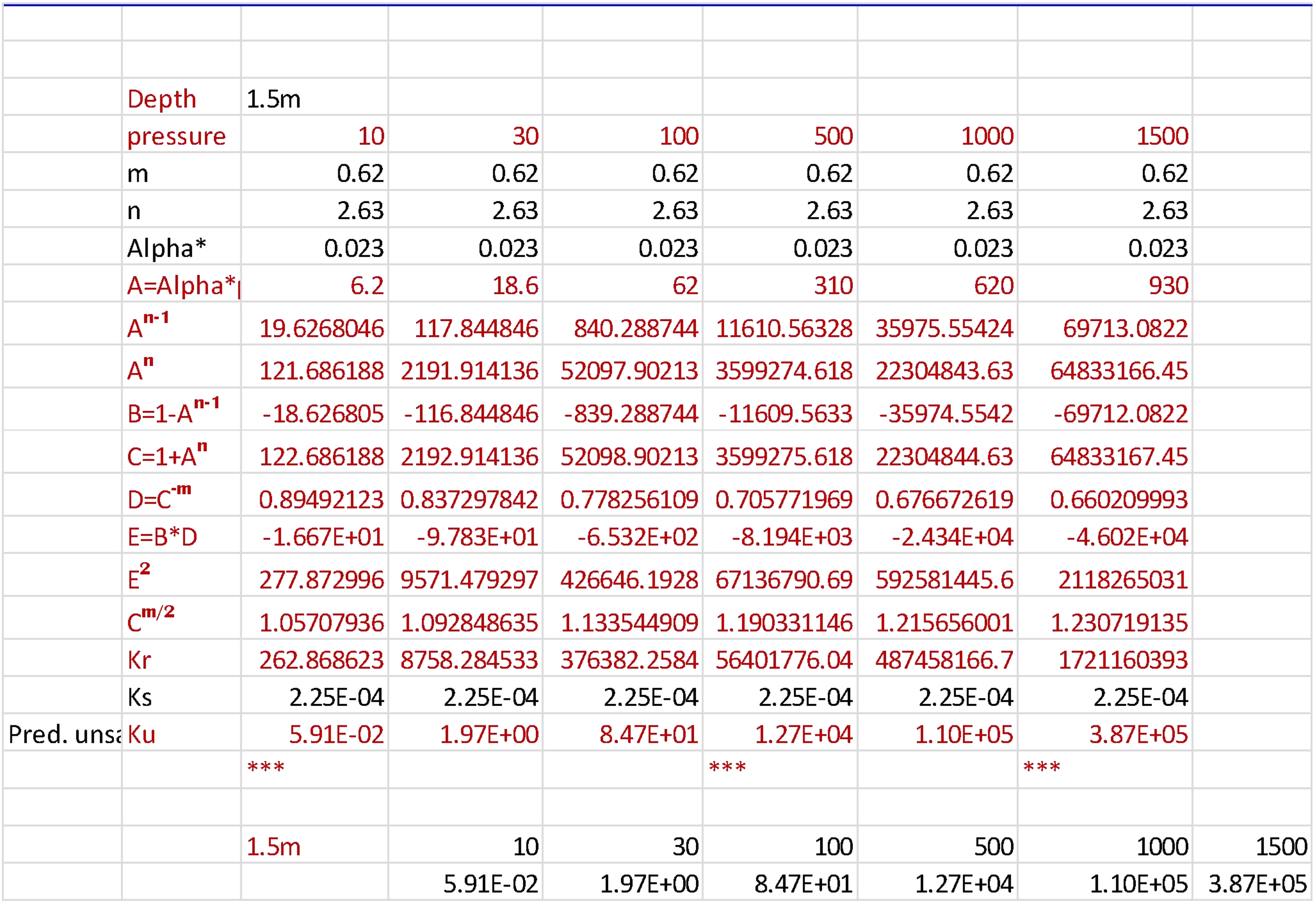


Figure 4.8: Predicted Ku with matric suction

Table 4.11: Prediction of unsaturated hydraulic conductivity (Ku) using Van genutchen Model for 1.5m depth (Basement Area)



	Depth	1.5m						
	pressure	10	30	100	500	1000	1500	
	m	0.62	0.62	0.62	0.62	0.62	0.62	
	n	2.63	2.63	2.63	2.63	2.63	2.63	
	Alpha*	0.023	0.023	0.023	0.023	0.023	0.023	
	A=Alpha*|	6.2	18.6	62	310	620	930	
	A^{n-1}	19.6268046	117.844846	840.288744	11610.56328	35975.55424	69713.0822	
	A^{n}	121.686188	2191.914136	52097.90213	3599274.618	22304843.63	64833166.45	
	B=1-A^{n-1}	-18.626805	-116.844846	-839.288744	-11609.5633	-35974.5542	-69712.0822	
	C=1+A^{n}	122.686188	2192.914136	52098.90213	3599275.618	22304844.63	64833167.45	
	D=C^{-m}	0.89492123	0.837297842	0.778256109	0.705771969	0.676672619	0.660209993	
	E=B*D	-1.667E+01	-9.783E+01	-6.532E+02	-8.194E+03	-2.434E+04	-4.602E+04	
	E^{2}	277.872996	9571.479297	426646.1928	67136790.69	592581445.6	2118265031	
	$C^{m/2}$	1.05707936	1.092848635	1.133544909	1.190331146	1.215656001	1.230719135	
	Kr	262.868623	8758.284533	376382.2584	56401776.04	487458166.7	1721160393	
	Ks	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	
Pred. unsa	Ku	5.91E-02	1.97E+00	8.47E+01	1.27E+04	1.10E+05	3.87E+05	
		***			***		***	
		1.5m	10	30	100	500	1000	1500
			5.91E-02	1.97E+00	8.47E+01	1.27E+04	1.10E+05	3.87E+05

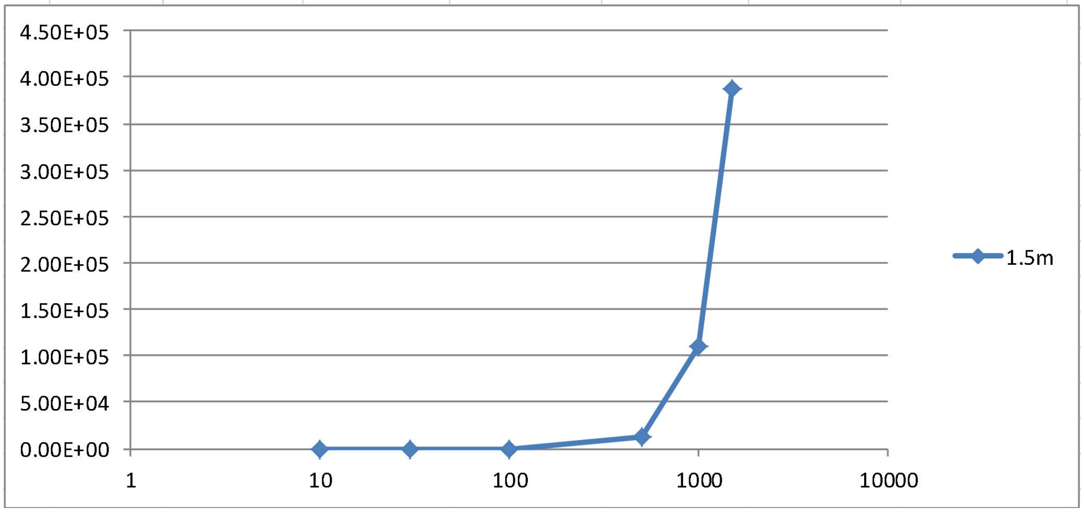
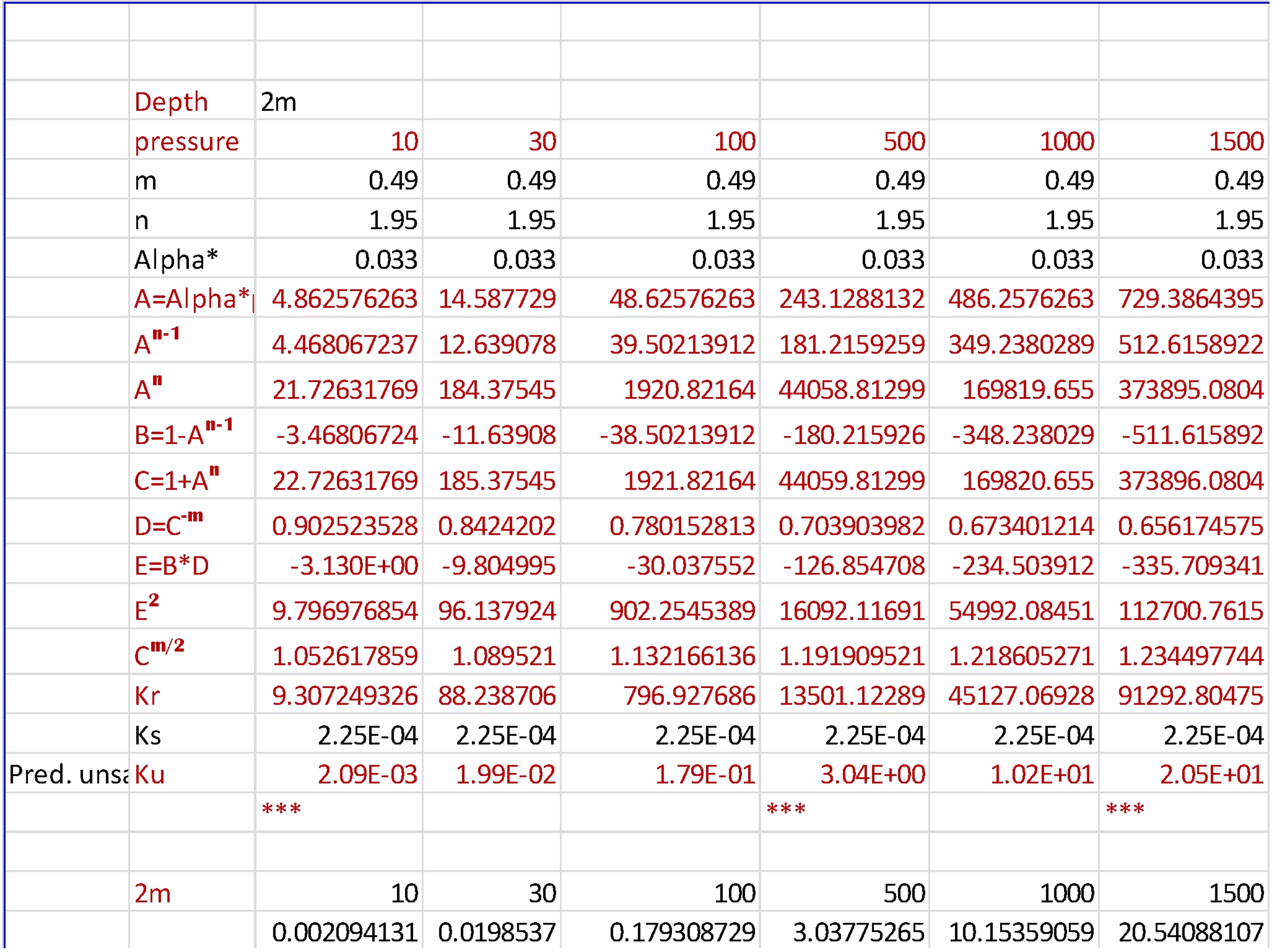


Figure 4.9: Predicted Ku with matric suction

Table 4.12: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen Model for 2.0m depth (Basement Area)



	Depth	2m					
	pressure	10	30	100	500	1000	1500
	m	0.49	0.49	0.49	0.49	0.49	0.49
	n	1.95	1.95	1.95	1.95	1.95	1.95
	Alpha*	0.033	0.033	0.033	0.033	0.033	0.033
	A=Alpha*	4.862576263	14.587729	48.62576263	243.1288132	486.2576263	729.3864395
	A^{n-1}	4.468067237	12.639078	39.50213912	181.2159259	349.2380289	512.6158922
	A^{n}	21.72631769	184.37545	1920.82164	44058.81299	169819.655	373895.0804
	$B=1-A^{n-1}$	-3.46806724	-11.63908	-38.50213912	-180.215926	-348.238029	-511.615892
	$C=1+A^{n}$	22.72631769	185.37545	1921.82164	44059.81299	169820.655	373896.0804
	$D=C^{-m}$	0.902523528	0.8424202	0.780152813	0.703903982	0.673401214	0.656174575
	E=B*D	-3.130E+00	-9.804995	-30.037552	-126.854708	-234.503912	-335.709341
	E^{2}	9.796976854	96.137924	902.2545389	16092.11691	54992.08451	112700.7615
	$C^{m/2}$	1.052617859	1.089521	1.132166136	1.191909521	1.218605271	1.234497744
	Kr	9.307249326	88.238706	796.927686	13501.12289	45127.06928	91292.80475
	Ks	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04
Pred. uns	Ku	2.09E-03	1.99E-02	1.79E-01	3.04E+00	1.02E+01	2.05E+01
		***			***		***
	2m	10	30	100	500	1000	1500
		0.002094131	0.0198537	0.179308729	3.03775265	10.15359059	20.54088107

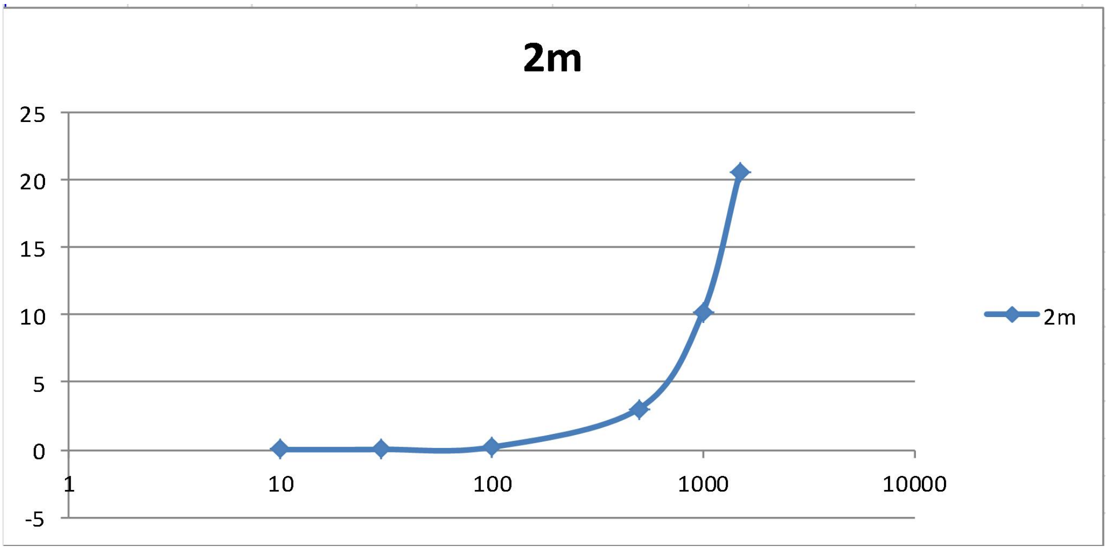


Figure 4.13: Predicted Ku with matric suction

Table 4.13: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen Model for 2.5m depth (Basement Area)

	Depth	2.5m					
	pressure	10	30	100	500	1000	1500
	m	0.14	0.14	0.14	0.14	0.14	0.14
	n	1.16	1.16	1.16	1.16	1.16	1.16
	Alpha*	0.331	0.331	0.331	0.331	0.331	0.331
	A=Alpha*	1.366476214	4.099428642	13.66476214	68.3238107	136.6476214	204.9714321
	A^{n-1}	1.050660732	1.250199028	1.512648801	1.951497543	2.177778541	2.322120031
	A^{n}	1.435702899	5.125101703	20.66998607	133.3337487	297.5882575	475.9682684
	$B=1-A^{n-1}$	-0.050660732	-0.250199028	-0.512648801	-0.951497543	-1.177778541	-1.322120031
	$C=1+A^{n}$	2.435702899	6.125101703	21.66998607	134.3337487	298.5882575	476.9682684
	$D=C^{-m}$	0.745011646	0.54921423	0.361659347	0.197841655	0.151921663	0.130124825
	E=B*D	-3.7742835E-02	-1.374129E-01	-1.8540423E-01	-1.8824585E-01	-1.7893007E-01	-1.7204064E-01
	E^{2}	0.001424522	0.018882296	0.034374729	0.035436499	0.032015971	0.029597981
	$C^{m/2}$	1.158559837	1.349363969	1.662838814	2.248232036	2.565607093	2.772170394
	Kr	0.001229562	0.013993479	0.020672316	0.01576194	0.012478907	0.010676826
	Ks	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
Pred. uns	Ku	1.77E-07	2.02E-06	2.98E-06	2.27E-06	1.80E-06	1.54E-06
		***			***		***
		10	30	100	500	1000	1500
		1.77057E-07	2.01506E-06	2.97681E-06	2.26972E-06	1.79696E-06	1.53746E-06

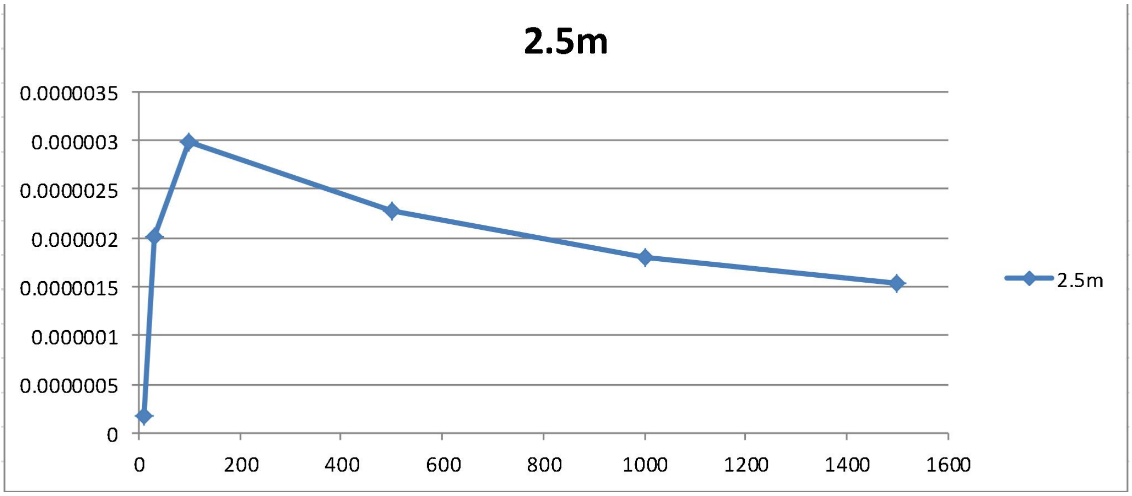
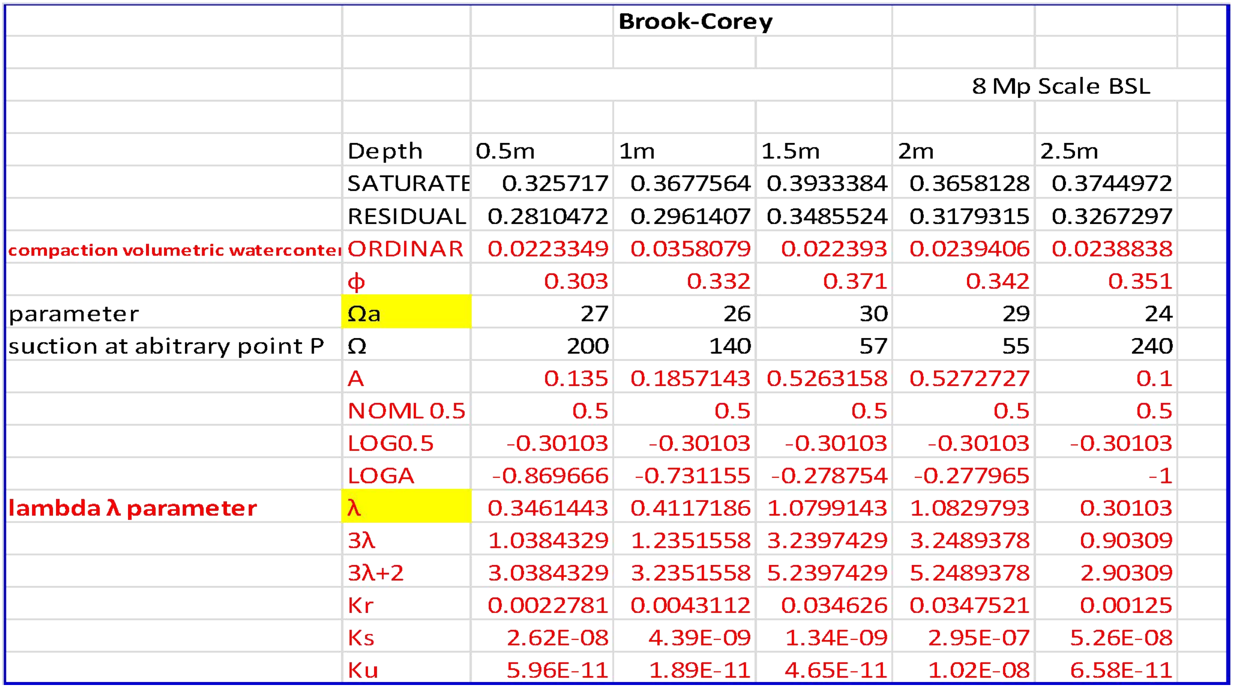


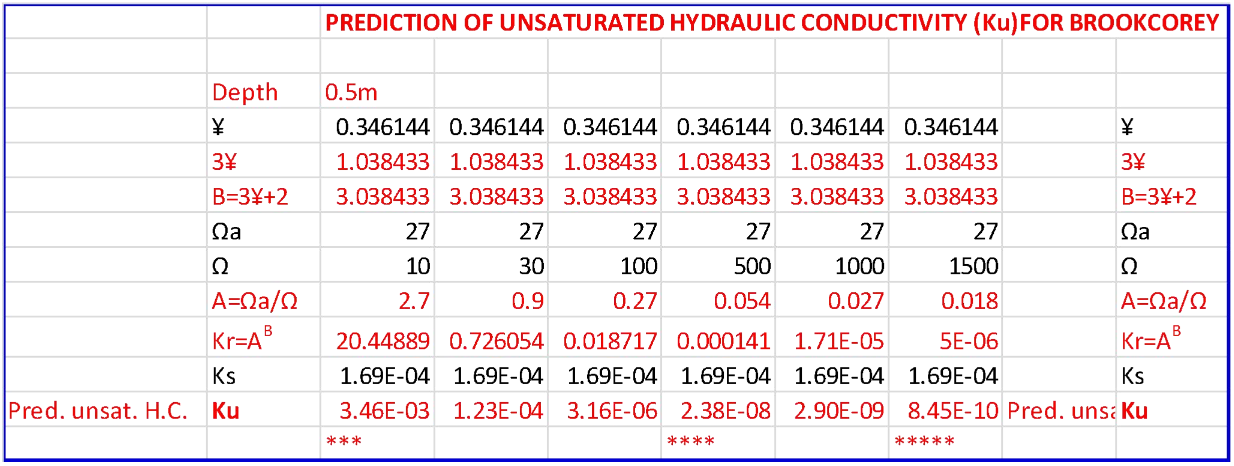
Figure 4.11: Predicted Ku with matric suction

Table 4.14: Brook-Corey Model using SWCC parameters (Basement Area)



			Brook-Corey			
					8 Mp Scale BSL	
	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATE	0.325717	0.3677564	0.3933384	0.3658128	0.3744972
	RESIDUAL	0.2810472	0.2961407	0.3485524	0.3179315	0.3267297
compaction volumetric watercontei	ORDINAR	0.0223349	0.0358079	0.022393	0.0239406	0.0238838
	ϕ	0.303	0.332	0.371	0.342	0.351
parameter	Ωa	27	26	30	29	24
suction at abitrary point P	Ω	200	140	57	55	240
	A	0.135	0.1857143	0.5263158	0.5272727	0.1
	NOML 0.5	0.5	0.5	0.5	0.5	0.5
	LOG0.5	-0.30103	-0.30103	-0.30103	-0.30103	-0.30103
	LOGA	-0.869666	-0.731155	-0.278754	-0.277965	-1
lambda λ parameter	λ	0.3461443	0.4117186	1.0799143	1.0829793	0.30103
	3λ	1.0384329	1.2351558	3.2397429	3.2489378	0.90309
	3λ+2	3.0384329	3.2351558	5.2397429	5.2489378	2.90309
	Kr	0.0022781	0.0043112	0.034626	0.0347521	0.00125
	Ks	2.62E-08	4.39E-09	1.34E-09	2.95E-07	5.26E-08
	Ku	5.96E-11	1.89E-11	4.65E-11	1.02E-08	6.58E-11

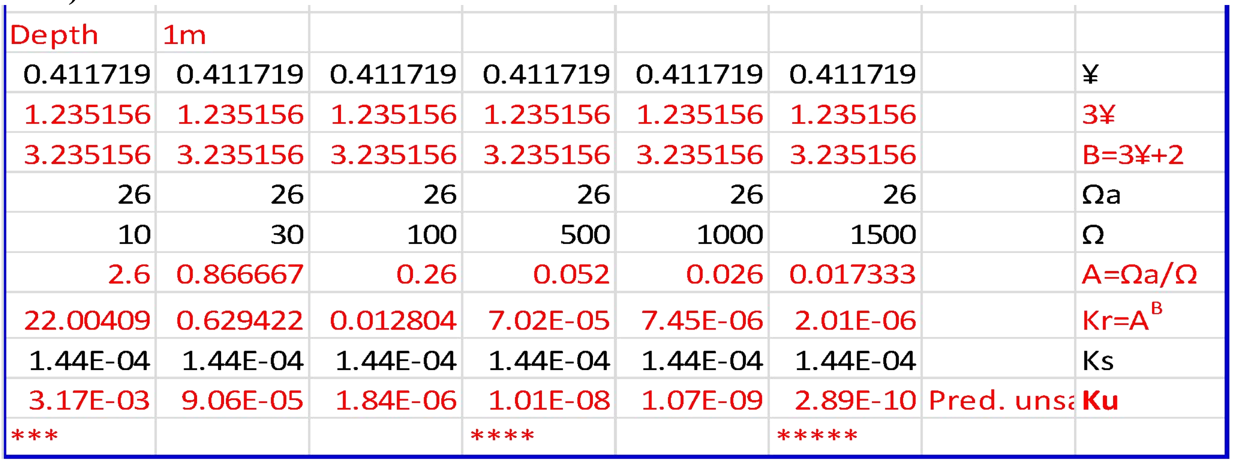
Table 4.15a: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey Model for 0.5m depth (Basement Area)



		PREDICTION OF UNSATURATED HYDRAULIC CONDUCTIVITY (Ku)FOR BROOKCOREY							
	Depth	0.5m							
	¥	0.346144	0.346144	0.346144	0.346144	0.346144	0.346144		¥
	3¥	1.038433	1.038433	1.038433	1.038433	1.038433	1.038433		3¥
	B=3¥+2	3.038433	3.038433	3.038433	3.038433	3.038433	3.038433		B=3¥+2
	Ωa	27	27	27	27	27	27		Ωa
	Ω	10	30	100	500	1000	1500		Ω
	A=Ωa/Ω	2.7	0.9	0.27	0.054	0.027	0.018		A=Ωa/Ω
	$Kr=A^B$	20.44889	0.726054	0.018717	0.000141	1.71E-05	5E-06		$Kr=A^B$
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04		Ks
Pred. unsat. H.C.	**Ku**	3.46E-03	1.23E-04	3.16E-06	2.38E-08	2.90E-09	8.45E-10	Pred. unsa	**Ku**
		***			****		*****		

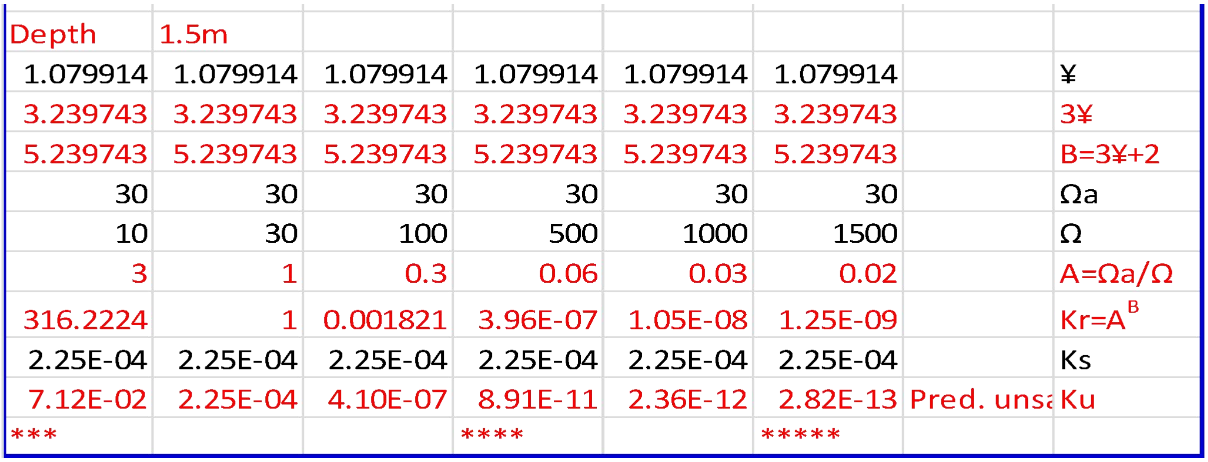
Table 4.15b: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey Model for 1.0m depth (Basement

Area)



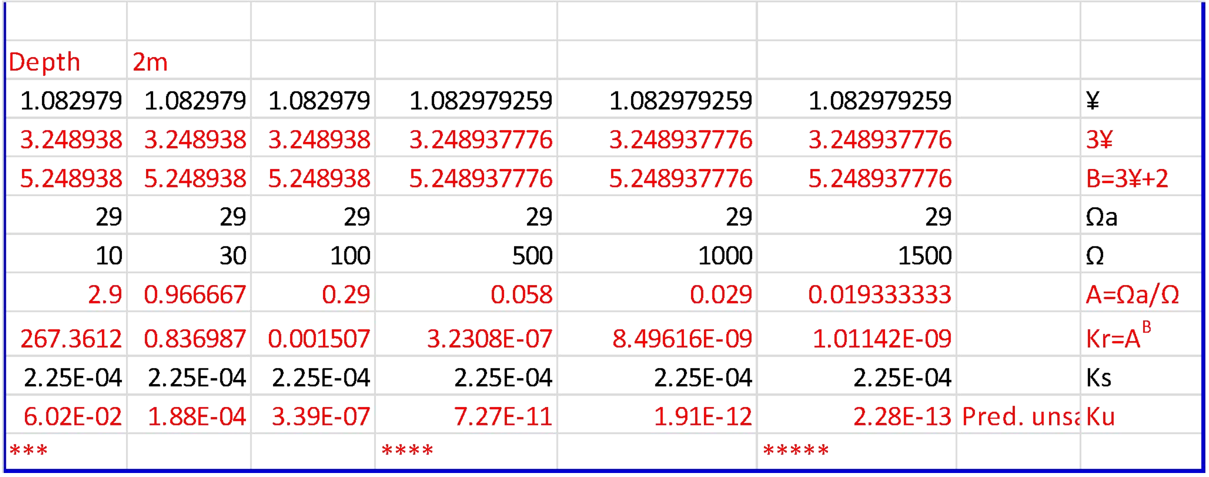
Depth	1m						
0.411719	0.411719	0.411719	0.411719	0.411719	0.411719		¥
1.235156	1.235156	1.235156	1.235156	1.235156	1.235156		3¥
3.235156	3.235156	3.235156	3.235156	3.235156	3.235156		B=3¥+2
26	26	26	26	26	26		Ωa
10	30	100	500	1000	1500		Ω
2.6	0.866667	0.26	0.052	0.026	0.017333		A=Ωa/Ω
22.00409	0.629422	0.012804	7.02E-05	7.45E-06	2.01E-06		Kr=A^{B}
1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04		Ks
3.17E-03	9.06E-05	1.84E-06	1.01E-08	1.07E-09	2.89E-10	Pred. unsa	**Ku**
***			****		*****		

Table 4.16: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey Model for 1.5m depth (Basement Area)



Depth	1.5m						
1.079914	1.079914	1.079914	1.079914	1.079914	1.079914		¥
3.239743	3.239743	3.239743	3.239743	3.239743	3.239743		3¥
5.239743	5.239743	5.239743	5.239743	5.239743	5.239743		B=3¥+2
30	30	30	30	30	30		Ωa
10	30	100	500	1000	1500		Ω
3	1	0.3	0.06	0.03	0.02		A=Ωa/Ω
316.2224	1	0.001821	3.96E-07	1.05E-08	1.25E-09		Kr=A^{B}
2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04		Ks
7.12E-02	2.25E-04	4.10E-07	8.91E-11	2.36E-12	2.82E-13	Pred. unsa	Ku
***			****		*****		

Table 4.17: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey Model for 2.0m depth (Basement Area)



Depth	2m						
1.082979	1.082979	1.082979	1.082979259	1.082979259	1.082979259		¥
3.248938	3.248938	3.248938	3.248937776	3.248937776	3.248937776		3¥
5.248938	5.248938	5.248938	5.248937776	5.248937776	5.248937776		B=3¥+2
29	29	29	29	29	29		Ωa
10	30	100	500	1000	1500		Ω
2.9	0.966667	0.29	0.058	0.029	0.019333333		A=Ωa/Ω
267.3612	0.836987	0.001507	3.2308E-07	8.49616E-09	1.01142E-09		Kr=A^{B}
2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04		Ks
6.02E-02	1.88E-04	3.39E-07	7.27E-11	1.91E-12	2.28E-13	Pred. unsa	Ku
***			****		*****		

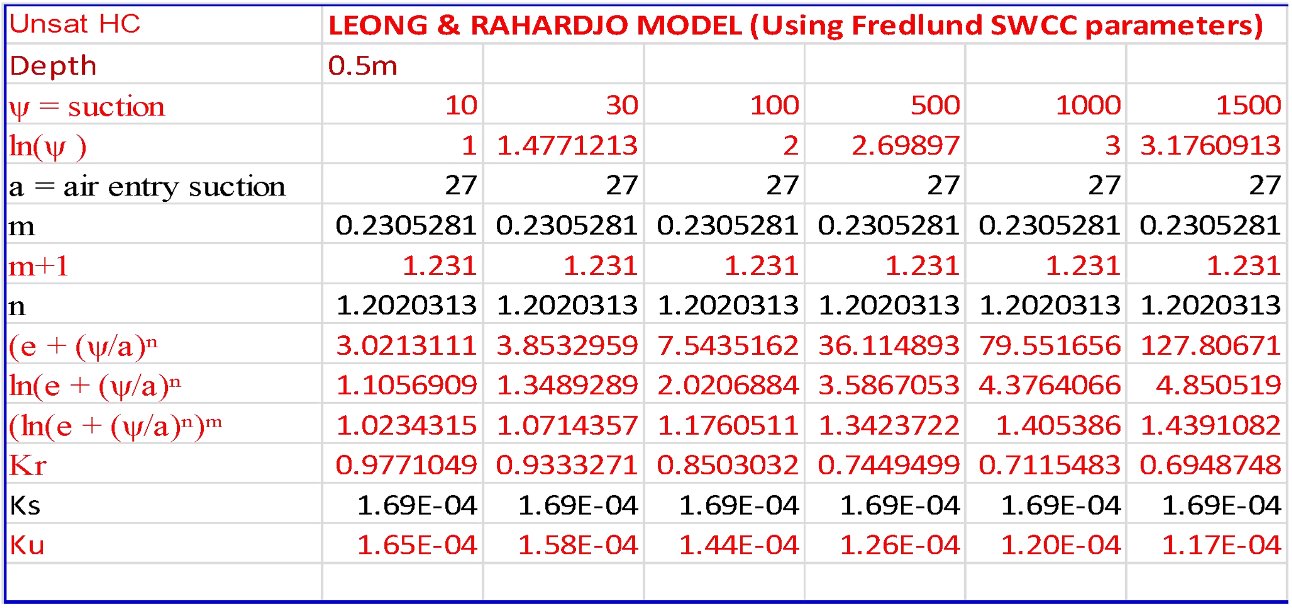
Table 4.18: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey Model for 2.5m depth (Basement Area)

Depth	2.5m				
0.30103	0.3493454	0.3493454	0.349345408	0.349345408	0.349345408
0.90309	1.0480362	1.0480362	1.048036225	1.048036225	1.048036225
2.90309	3.0480362	3.0480362	3.048036225	3.048036225	3.048036225
24	24	24	24	24	24
10	30	100	500	1000	1500
2.4	0.8	0.24	0.048	0.024	0.016
12.699524	0.5065412	0.0129081	9.55819E-05	1.15565E-05	3.35809E-06
1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
1.83E-03	7.29E-05	1.86E-06	1.38E-08	1.66E-09	4.84E-10
***			****		*****

Table 4.19: Fredlund and Xing Model using SWCC parameters (Basement Area)

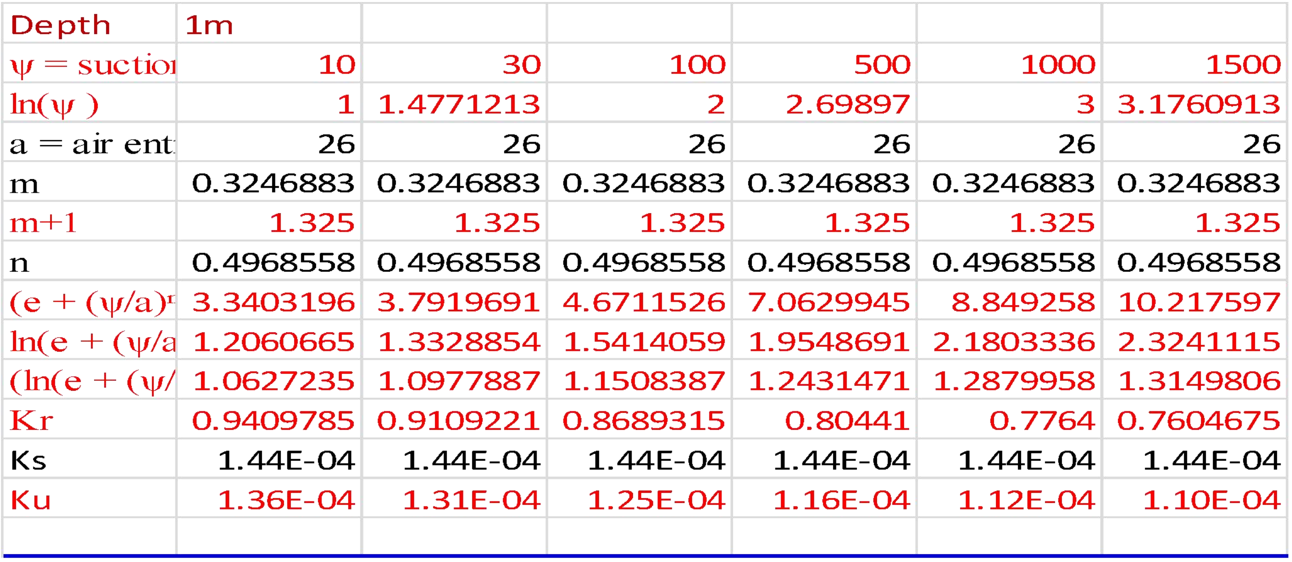
LEONG & RAHARDJO MODEL (Using Fredlund SWCC parameters)						
	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATE	0.325717	0.367756	0.393338	0.365813	0.374497
	RESIDUAL	0.281047	0.296141	0.348552	0.317932	0.32673
compaction volumetric wate	ORDINAR	0.022335	0.035808	0.022393	0.023941	0.023884
Residual Suction (Ωr)	(Ωr)	1500	1500	1500	1500	1500
Suction @ air entry	Ωa	27	26	30	29	24
Suction @ P	**Ωi = a=A**	200	140	57	55	240
	Y1	0.296	0.332	0.366	0.342	0.337
	Y2	0.3118	0.344	0.382	0.354	0.341
	X1	2	1.69897	1.60206	1.60206	2.146128
	X2	2.69897	2.477121	1.90309	1.90309	2.60206
	SLOPE	0.022605	0.015421	0.053151	0.039863	0.008773
	(Ωr) + (Ωi)	1700	1640	1557	1555	1740
Vol water cont. @ P	θ	0.300	0.332	0.373	0.347	0.3384
	Numi	-0.12516	-0.08923	-0.0373	-0.03601	-0.14842
	Denomi	6.503789	6.503789	6.503789	6.503789	6.503789
	C(Ω)	0.980755	0.98628	0.994266	0.994463	0.977179
B	m*	0.231	0.325	0.174	0.173	0.287
	m*+1	1.231	1.325	1.174	1.173	1.287
	B	0.016997	0.012024	0.005371	0.00519	0.019625
	s*	0.052	0.030	0.130	0.104	0.004
C	n*	1.202	0.497	3.836	3.074	0.071

Table 4.20: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlund and Xing for 0.5m depth (Basement Area)



Unsat HC	LEONG & RAHARDJO MODEL (Using Fredlund SWCC parameters)					
Depth	0.5m					
ψ = suction	10	30	100	500	1000	1500
$\ln(\psi)$	1	1.4771213	2	2.69897	3	3.1760913
a = air entry suction	27	27	27	27	27	27
m	0.2305281	0.2305281	0.2305281	0.2305281	0.2305281	0.2305281
m+1	1.231	1.231	1.231	1.231	1.231	1.231
n	1.2020313	1.2020313	1.2020313	1.2020313	1.2020313	1.2020313
$(e + (\psi/a)^n$	3.0213111	3.8532959	7.5435162	36.114893	79.551656	127.80671
$\ln(e + (\psi/a)^n$	1.1056909	1.3489289	2.0206884	3.5867053	4.3764066	4.850519
$(\ln(e + (\psi/a)^n)^m$	1.0234315	1.0714357	1.1760511	1.3423722	1.405386	1.4391082
Kr	0.9771049	0.9333271	0.8503032	0.7449499	0.7115483	0.6948748
Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Ku	1.65E-04	1.58E-04	1.44E-04	1.26E-04	1.20E-04	1.17E-04

Table 4.21: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlund and Xing for 1.0m depth (Basement Area)



Depth	1m					
ψ = suctio	10	30	100	500	1000	1500
$\ln(\psi)$	1	1.4771213	2	2.69897	3	3.1760913
a = air ent	26	26	26	26	26	26
m	0.3246883	0.3246883	0.3246883	0.3246883	0.3246883	0.3246883
m+1	1.325	1.325	1.325	1.325	1.325	1.325
n	0.4968558	0.4968558	0.4968558	0.4968558	0.4968558	0.4968558
$(e + (\psi/a)^n$	3.3403196	3.7919691	4.6711526	7.0629945	8.849258	10.217597
$\ln(e + (\psi/a$	1.2060665	1.3328854	1.5414059	1.9548691	2.1803336	2.3241115
$(\ln(e + (\psi/$	1.0627235	1.0977887	1.1508387	1.2431471	1.2879958	1.3149806
Kr	0.9409785	0.9109221	0.8689315	0.80441	0.7764	0.7604675
Ks	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
Ku	1.36E-04	1.31E-04	1.25E-04	1.16E-04	1.12E-04	1.10E-04

Table 4.22: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlund and Xing for 1.5m depth (Basement Area)

Depth	1.5m					
ψ = suctio	10	30	100	500	1000	1500
ln(ψ)	1	1.4771213	2	2.69897	3	3.176091
a = air ent	30	30	30	30	30	30
m	0.1737415	0.1737415	0.1737415	0.173742	0.173742	0.173742
m+1	1.174	1.174	1.174	1.174	1.174	1.174
n	3.8363015	3.8363015	3.8363015	3.836301	3.836301	3.836301
(e + (ψ/a)^{n}	2.7330581	3.71828	104.09086	48686.04	695382.4	3294288
ln(e + (ψ/a	1.0054212	1.3132612	4.6452642	10.79315	13.45222	15.0077
(ln(e + (ψ/	1.0009398	1.0484857	1.3058323	1.511822	1.570791	1.600938
Kr	0.9990611	0.9537565	0.7657951	0.661453	0.636622	0.624634
Ks	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04
Ku	2.25E-04	2.15E-04	1.72E-04	1.49E-04	1.43E-04	1.41E-04

Table 4.23: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlund and Xing for 2.0m depth (Basement Area)

Depth	2m					
ψ = suctio	10	30	100	500	1000	1500
ln(ψ)	1	1.477121	2	2.69897	3	3.176091
a = air ent	29	29	29	29	29	29
m	0.173388	0.173388	0.173388	0.173388	0.173388	0.173388
m+1	1.173	1.173	1.173	1.173	1.173	1.173
n	3.073705	3.073705	3.073705	3.073705	3.073705	3.073705
(e + (ψ/a)^{n}	2.756187	3.828106	47.63727	6324.765	53230.1	185094.8
ln(e + (ψ/a	1.013848	1.34237	3.863616	8.752228	10.88238	12.12862
(ln(e + (ψ/	1.002388	1.052377	1.264089	1.456638	1.512708	1.541415
Kr	0.997618	0.95023	0.791084	0.686512	0.661066	0.648755
Ks	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04
Ku	2.24E-04	2.14E-04	1.78E-04	1.54E-04	1.49E-04	1.46E-04

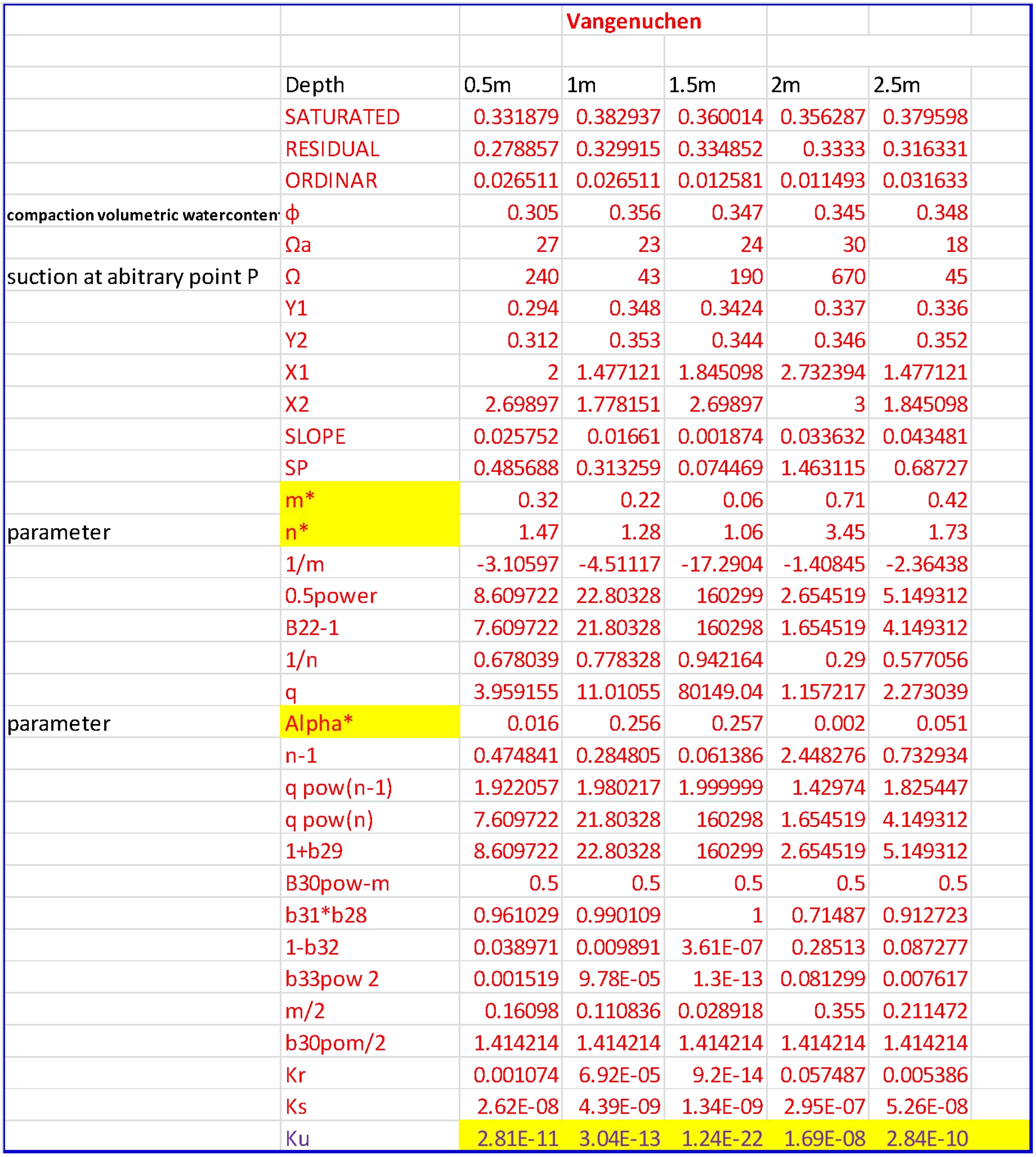
Table 4.24: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlund and Xing for 2.5m depth (Basement Area)

Depth	2.5m					
ψ = suctio	10	30	100	500	1000	1500
ln(ψ)	1	1.477121	2	2.69897	3	3.176091
a = air ent	24	24	24	24	24	24
m	0.287254	0.287254	0.287254	0.287254	0.287254	0.287254
m+1	1.287	1.287	1.287	1.287	1.287	1.287
n	0.071325	0.071325	0.071325	0.071325	0.071325	0.071325
(e + (ψ/a)^{n}	3.657746	3.734323	3.825431	3.960107	4.023044	4.061329
ln(e + (ψ/a	1.296847	1.317567	1.341671	1.376271	1.392039	1.40151
(ln(e + (ψ/	1.077526	1.082443	1.088095	1.096082	1.099675	1.101819
Kr	0.928052	0.923836	0.919037	0.91234	0.90936	0.90759
Ks	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
Ku	1.34E-04	1.33E-04	1.32E-04	1.31E-04	1.31E-04	1.31E-04

The three models that were used for prediction of hydraulic conductivity at various depths at basement location was repeated here at the faculty of education. Below are the results.

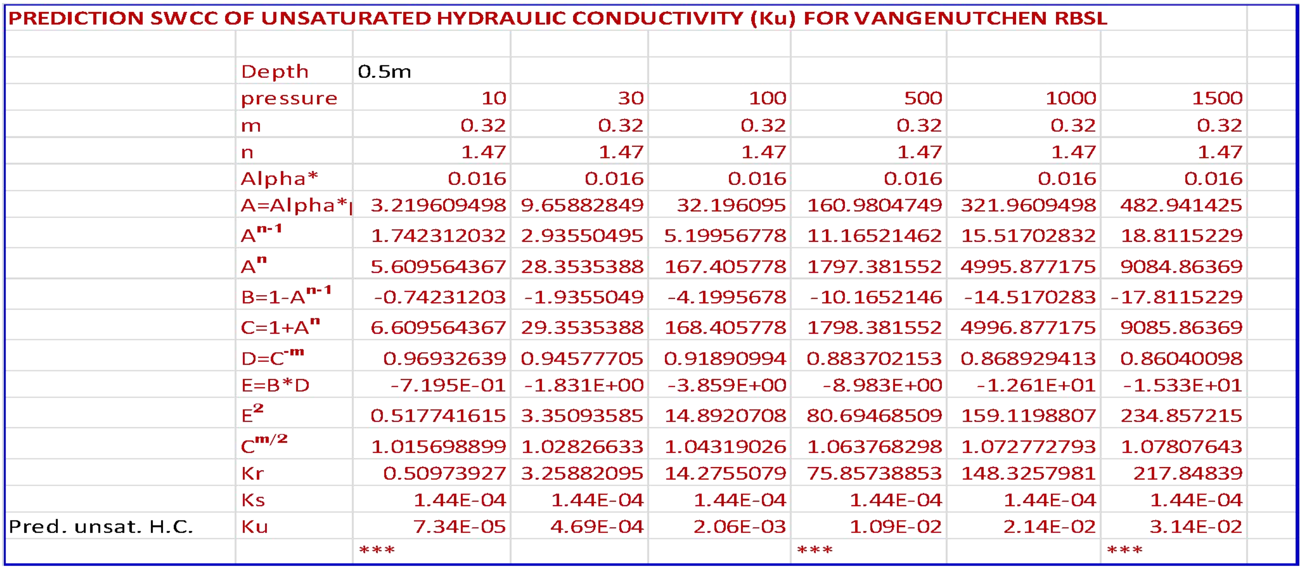
PREDICTION OF HYDRAULIC CONDUCTIVITY USING (VAN-GENUTCHEN, BROOK-COREY AND FREDLUND AND XING MODELS) FOR FACULTY OF EDUCATION AREA)

Table 4.25: Vangenutchen model using SWCC parameters (Faculty of Education Area)



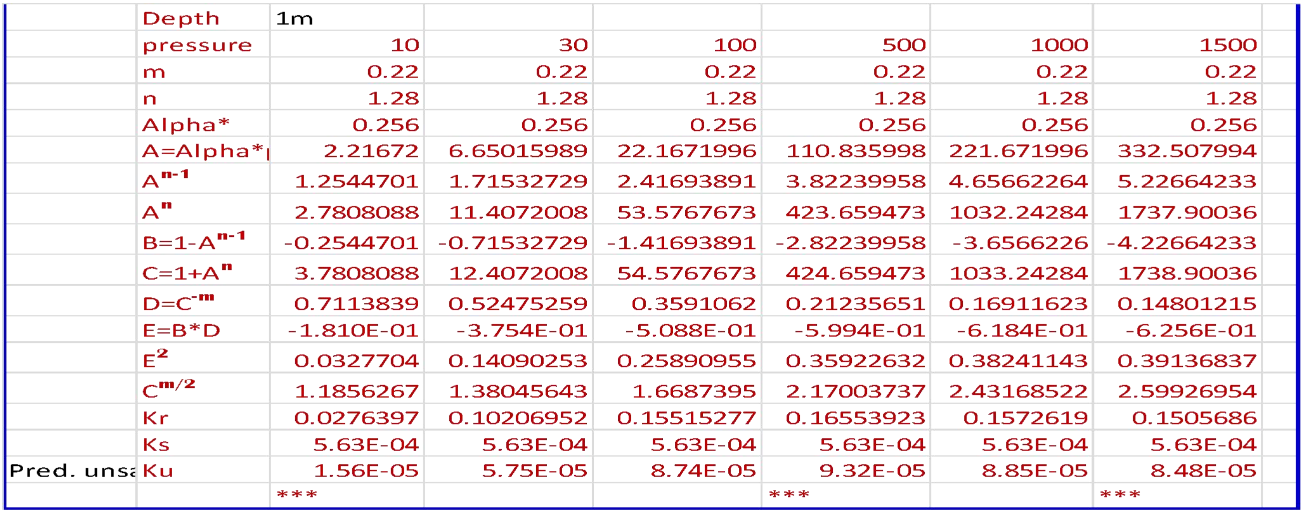
			Vangenuchen			
	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATED	0.331879	0.382937	0.360014	0.356287	0.379598
	RESIDUAL	0.278857	0.329915	0.334852	0.3333	0.316331
	ORDINAR	0.026511	0.026511	0.012581	0.011493	0.031633
compaction volumetric waterconten	ϕ	0.305	0.356	0.347	0.345	0.348
	Ωa	27	23	24	30	18
suction at abitrary point P	Ω	240	43	190	670	45
	Y1	0.294	0.348	0.3424	0.337	0.336
	Y2	0.312	0.353	0.344	0.346	0.352
	X1	2	1.477121	1.845098	2.732394	1.477121
	X2	2.69897	1.778151	2.69897	3	1.845098
	SLOPE	0.025752	0.01661	0.001874	0.033632	0.043481
	SP	0.485688	0.313259	0.074469	1.463115	0.68727
	m*	0.32	0.22	0.06	0.71	0.42
parameter	n*	1.47	1.28	1.06	3.45	1.73
	1/m	-3.10597	-4.51117	-17.2904	-1.40845	-2.36438
	0.5power	8.609722	22.80328	160299	2.654519	5.149312
	B22-1	7.609722	21.80328	160298	1.654519	4.149312
	1/n	0.678039	0.778328	0.942164	0.29	0.577056
	q	3.959155	11.01055	80149.04	1.157217	2.273039
parameter	Alpha*	0.016	0.256	0.257	0.002	0.051
	n-1	0.474841	0.284805	0.061386	2.448276	0.732934
	q pow(n-1)	1.922057	1.980217	1.999999	1.42974	1.825447
	q pow(n)	7.609722	21.80328	160298	1.654519	4.149312
	1+b29	8.609722	22.80328	160299	2.654519	5.149312
	B30pow-m	0.5	0.5	0.5	0.5	0.5
	b31*b28	0.961029	0.990109	1	0.71487	0.912723
	1-b32	0.038971	0.009891	3.61E-07	0.28513	0.087277
	b33pow 2	0.001519	9.78E-05	1.3E-13	0.081299	0.007617
	m/2	0.16098	0.110836	0.028918	0.355	0.211472
	b30pom/2	1.414214	1.414214	1.414214	1.414214	1.414214
	Kr	0.001074	6.92E-05	9.2E-14	0.057487	0.005386
	Ks	2.62E-08	4.39E-09	1.34E-09	2.95E-07	5.26E-08
	Ku	2.81E-11	3.04E-13	1.24E-22	1.69E-08	2.84E-10

Table 4.26: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 0.5m depth (Faculty of Education Area)



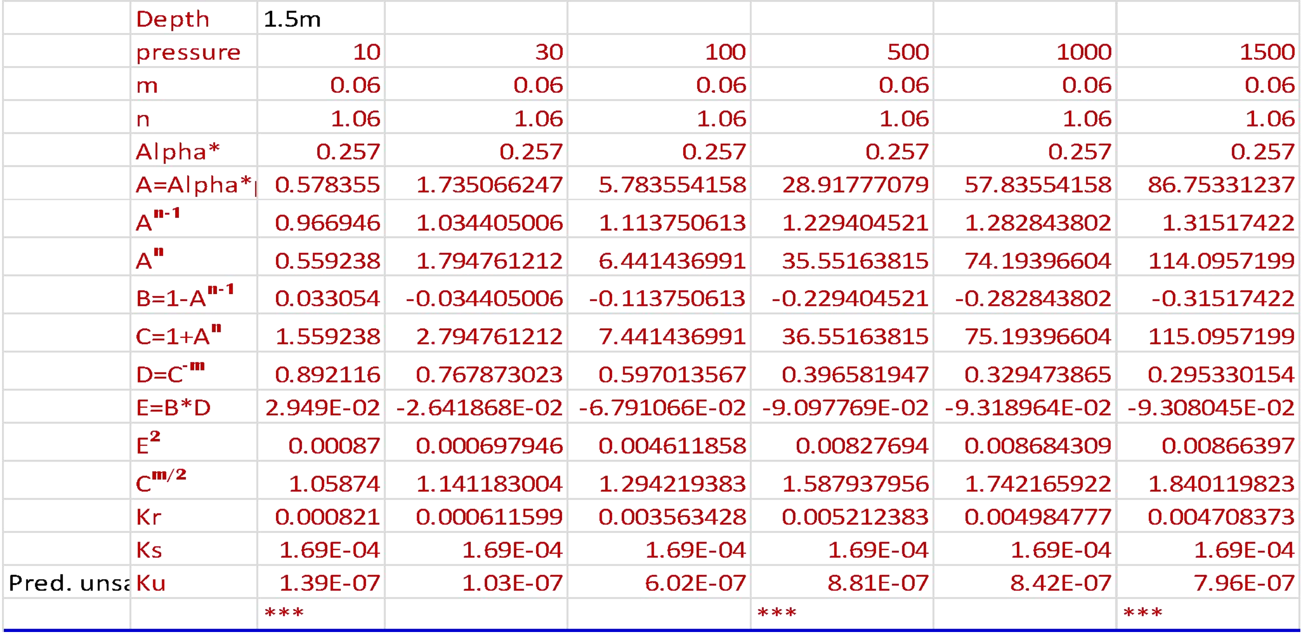
PREDICTION SWCC OF UNSATURATED HYDRAULIC CONDUCTIVITY (Ku) FOR VANGENUTCHEN RBSL							
	Depth	0.5m					
	pressure	10	30	100	500	1000	1500
	m	0.32	0.32	0.32	0.32	0.32	0.32
	n	1.47	1.47	1.47	1.47	1.47	1.47
	Alpha*	0.016	0.016	0.016	0.016	0.016	0.016
	A=Alpha*	3.219609498	9.65882849	32.196095	160.9804749	321.9609498	482.941425
	A^{n-1}	1.742312032	2.93550495	5.19956778	11.16521462	15.51702832	18.8115229
	A^{n}	5.609564367	28.3535388	167.405778	1797.381552	4995.877175	9084.86369
	$B=1-A^{n-1}$	-0.74231203	-1.9355049	-4.1995678	-10.1652146	-14.5170283	-17.8115229
	$C=1+A^{n}$	6.609564367	29.3535388	168.405778	1798.381552	4996.877175	9085.86369
	$D=C^{-m}$	0.96932639	0.94577705	0.91890994	0.883702153	0.868929413	0.86040098
	E=B*D	-7.195E-01	-1.831E+00	-3.859E+00	-8.983E+00	-1.261E+01	-1.533E+01
	E^{2}	0.517741615	3.35093585	14.8920708	80.69468509	159.1198807	234.857215
	$C^{m/2}$	1.015698899	1.02826633	1.04319026	1.063768298	1.072772793	1.07807643
	Kr	0.50973927	3.25882095	14.2755079	75.85738853	148.3257981	217.84839
	Ks	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
Pred. unsat. H.C.	Ku	7.34E-05	4.69E-04	2.06E-03	1.09E-02	2.14E-02	3.14E-02
		***			***		***

Table 4.27: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 1.0m depth (Faculty of Education Area)



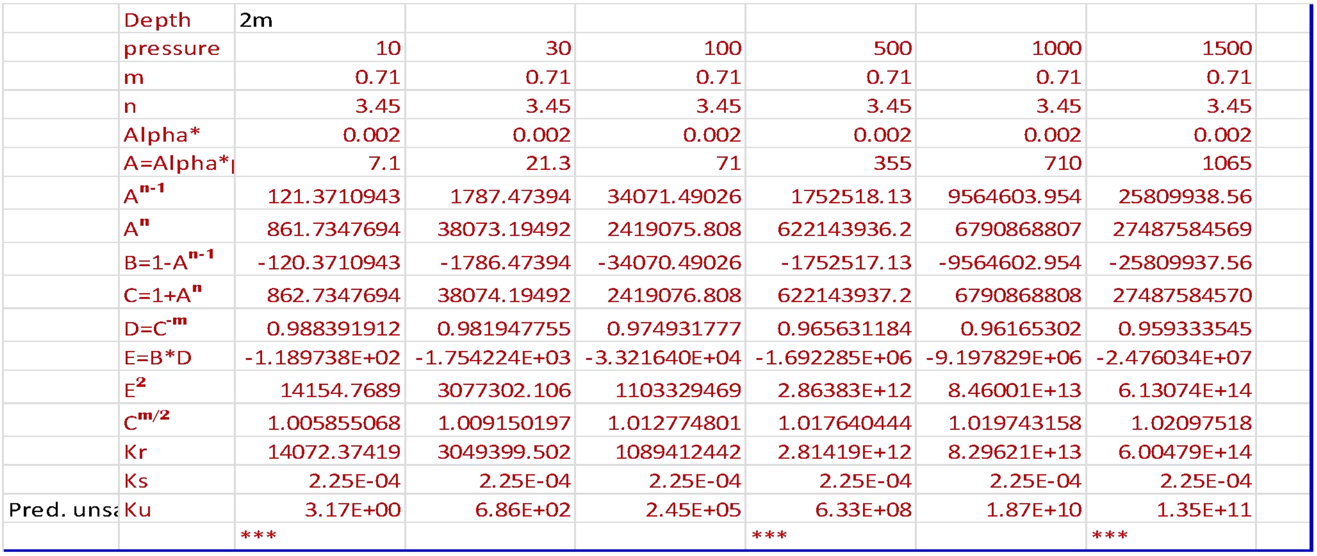
	Depth	1m					
	pressure	10	30	100	500	1000	1500
	m	0.22	0.22	0.22	0.22	0.22	0.22
	n	1.28	1.28	1.28	1.28	1.28	1.28
	Alpha*	0.256	0.256	0.256	0.256	0.256	0.256
	A=Alpha*	2.21672	6.65015989	22.1671996	110.835998	221.671996	332.507994
	A^{n-1}	1.2544701	1.71532729	2.41693891	3.82239958	4.65662264	5.22664233
	A^{n}	2.7808088	11.4072008	53.5767673	423.659473	1032.24284	1737.90036
	$B=1-A^{n-1}$	-0.2544701	-0.71532729	-1.41693891	-2.82239958	-3.6566226	-4.22664233
	$C=1+A^{n}$	3.7808088	12.4072008	54.5767673	424.659473	1033.24284	1738.90036
	$D=C^{-m}$	0.7113839	0.52475259	0.3591062	0.21235651	0.16911623	0.14801215
	E=B*D	-1.810E-01	-3.754E-01	-5.088E-01	-5.994E-01	-6.184E-01	-6.256E-01
	E^{2}	0.0327704	0.14090253	0.25890955	0.35922632	0.38241143	0.39136837
	$C^{m/2}$	1.1856267	1.38045643	1.6687395	2.17003737	2.43168522	2.59926954
	Kr	0.0276397	0.10206952	0.15515277	0.16553923	0.1572619	0.1505686
	Ks	5.63E-04	5.63E-04	5.63E-04	5.63E-04	5.63E-04	5.63E-04
Pred. unsa	Ku	1.56E-05	5.75E-05	8.74E-05	9.32E-05	8.85E-05	8.48E-05
		***			***		***

Table 4.28: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 1.5m depth (Faculty of Education Area)



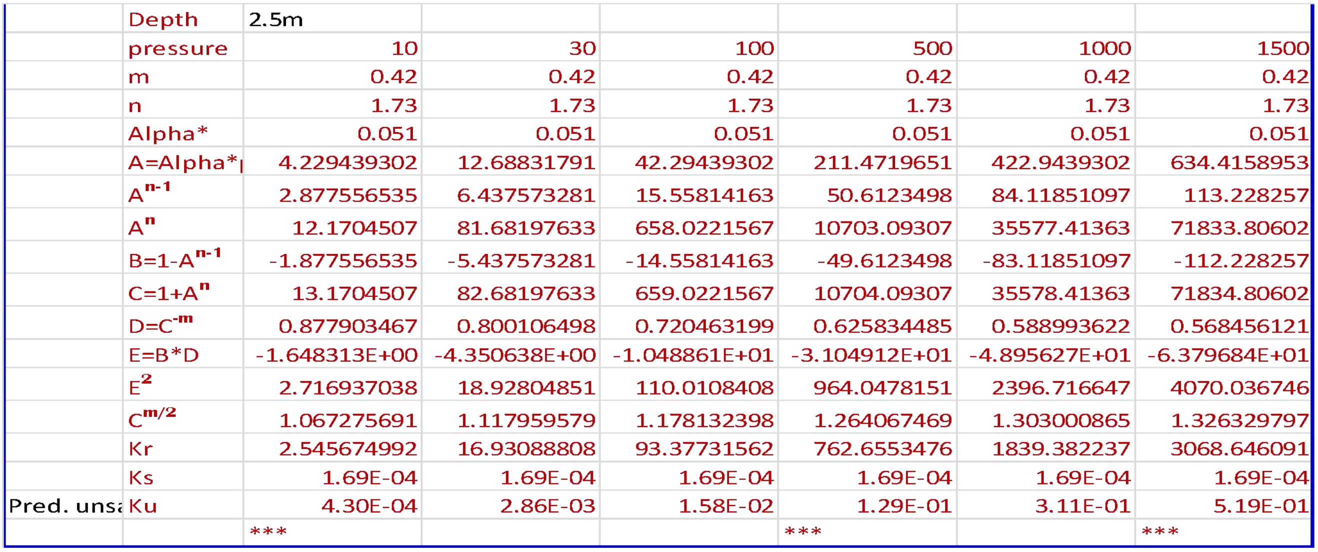
	Depth	1.5m					
	pressure	10	30	100	500	1000	1500
	m	0.06	0.06	0.06	0.06	0.06	0.06
	n	1.06	1.06	1.06	1.06	1.06	1.06
	Alpha*	0.257	0.257	0.257	0.257	0.257	0.257
	A=Alpha*|	0.578355	1.735066247	5.783554158	28.91777079	57.83554158	86.75331237
	A^{n-1}	0.966946	1.034405006	1.113750613	1.229404521	1.282843802	1.31517422
	A^{n}	0.559238	1.794761212	6.441436991	35.55163815	74.19396604	114.0957199
	$B=1-A^{n-1}$	0.033054	-0.034405006	-0.113750613	-0.229404521	-0.282843802	-0.31517422
	$C=1+A^{n}$	1.559238	2.794761212	7.441436991	36.55163815	75.19396604	115.0957199
	$D=C^{-m}$	0.892116	0.767873023	0.597013567	0.396581947	0.329473865	0.295330154
	E=B*D	2.949E-02	-2.641868E-02	-6.791066E-02	-9.097769E-02	-9.318964E-02	-9.308045E-02
	E^{2}	0.00087	0.000697946	0.004611858	0.00827694	0.008684309	0.00866397
	$C^{m/2}$	1.05874	1.141183004	1.294219383	1.587937956	1.742165922	1.840119823
	Kr	0.000821	0.000611599	0.003563428	0.005212383	0.004984777	0.004708373
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Pred. unsa	Ku	1.39E-07	1.03E-07	6.02E-07	8.81E-07	8.42E-07	7.96E-07
		***			***		***

Table 4.29: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 2.0m depth (Faculty of Education Area)



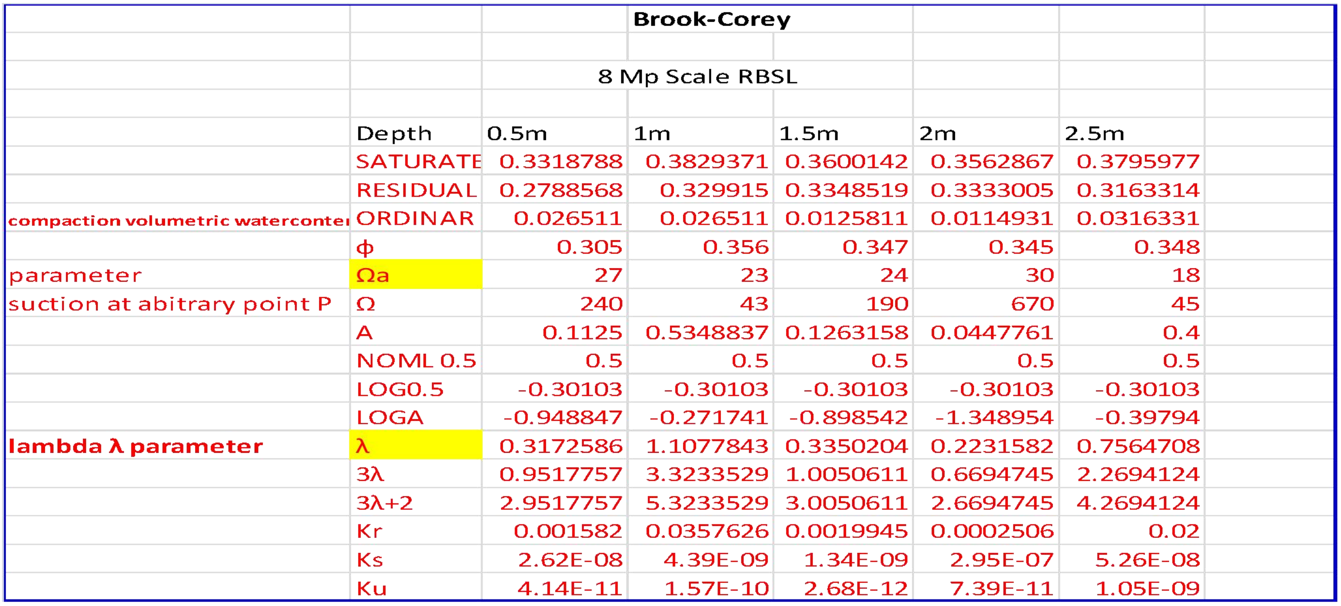
	Depth	2m					
	pressure	10	30	100	500	1000	1500
	m	0.71	0.71	0.71	0.71	0.71	0.71
	n	3.45	3.45	3.45	3.45	3.45	3.45
	Alpha*	0.002	0.002	0.002	0.002	0.002	0.002
	A=Alpha*|	7.1	21.3	71	355	710	1065
	A^{n-1}	121.3710943	1787.47394	34071.49026	1752518.13	9564603.954	25809938.56
	A^{n}	861.7347694	38073.19492	2419075.808	622143936.2	6790868807	27487584569
	$B=1-A^{n-1}$	-120.3710943	-1786.47394	-34070.49026	-1752517.13	-9564602.954	-25809937.56
	$C=1+A^{n}$	862.7347694	38074.19492	2419076.808	622143937.2	6790868808	27487584570
	$D=C^{-m}$	0.988391912	0.981947755	0.974931777	0.965631184	0.96165302	0.959333545
	E=B*D	-1.189738E+02	-1.754224E+03	-3.321640E+04	-1.692285E+06	-9.197829E+06	-2.476034E+07
	E^{2}	14154.7689	3077302.106	1103329469	2.86383E+12	8.46001E+13	6.13074E+14
	$C^{m/2}$	1.005855068	1.009150197	1.012774801	1.017640444	1.019743158	1.02097518
	Kr	14072.37419	3049399.502	1089412442	2.81419E+12	8.29621E+13	6.00479E+14
	Ks	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04
Pred. unsa	Ku	3.17E+00	6.86E+02	2.45E+05	6.33E+08	1.87E+10	1.35E+11
		***			***		***

Table 4.30: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 2.5m depth (Faculty of Education Area)



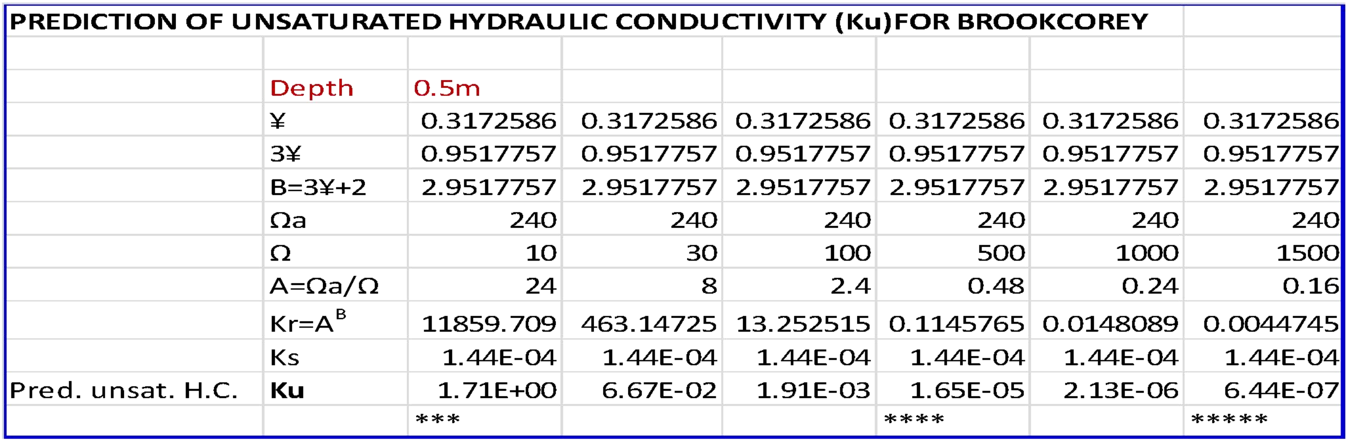
	Depth	2.5m					
	pressure	10	30	100	500	1000	1500
	m	0.42	0.42	0.42	0.42	0.42	0.42
	n	1.73	1.73	1.73	1.73	1.73	1.73
	Alpha*	0.051	0.051	0.051	0.051	0.051	0.051
	A=Alpha*I	4.229439302	12.68831791	42.29439302	211.4719651	422.9439302	634.4158953
	A^{n-1}	2.877556535	6.437573281	15.55814163	50.6123498	84.11851097	113.228257
	A^{n}	12.1704507	81.68197633	658.0221567	10703.09307	35577.41363	71833.80602
	$B=1-A^{n-1}$	-1.877556535	-5.437573281	-14.55814163	-49.6123498	-83.11851097	-112.228257
	$C=1+A^{n}$	13.1704507	82.68197633	659.0221567	10704.09307	35578.41363	71834.80602
	$D=C^{-m}$	0.877903467	0.800106498	0.720463199	0.625834485	0.588993622	0.568456121
	E=B*D	-1.648313E+00	-4.350638E+00	-1.048861E+01	-3.104912E+01	-4.895627E+01	-6.379684E+01
	E^{2}	2.716937038	18.92804851	110.0108408	964.0478151	2396.716647	4070.036746
	$C^{m/2}$	1.067275691	1.117959579	1.178132398	1.264067469	1.303000865	1.326329797
	Kr	2.545674992	16.93088808	93.37731562	762.6553476	1839.382237	3068.646091
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Pred. unsa	Ku	4.30E-04	2.86E-03	1.58E-02	1.29E-01	3.11E-01	5.19E-01
		***			***		***

Table 4.31: Brook-Corey model using SWCC parameters (Faculty of Education Area)



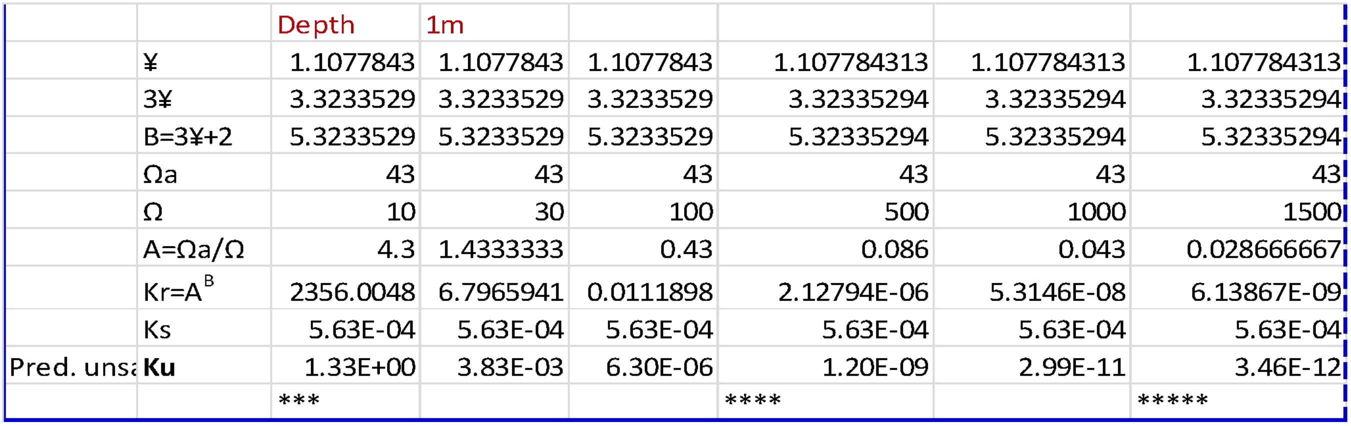
			Brook-Corey			
		8 Mp Scale RBSL				
	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATE	0.3318788	0.3829371	0.3600142	0.3562867	0.3795977
	RESIDUAL	0.2788568	0.329915	0.3348519	0.3333005	0.3163314
compaction volumetric watercontei	ORDINAR	0.026511	0.026511	0.0125811	0.0114931	0.0316331
	ф	0.305	0.356	0.347	0.345	0.348
parameter	Ωa	27	23	24	30	18
suction at abitrary point P	Ω	240	43	190	670	45
	A	0.1125	0.5348837	0.1263158	0.0447761	0.4
	NOML 0.5	0.5	0.5	0.5	0.5	0.5
	LOG0.5	-0.30103	-0.30103	-0.30103	-0.30103	-0.30103
	LOGA	-0.948847	-0.271741	-0.898542	-1.348954	-0.39794
lambda λ parameter	λ	0.3172586	1.1077843	0.3350204	0.2231582	0.7564708
	3λ	0.9517757	3.3233529	1.0050611	0.6694745	2.2694124
	3λ+2	2.9517757	5.3233529	3.0050611	2.6694745	4.2694124
	Kr	0.001582	0.0357626	0.0019945	0.0002506	0.02
	Ks	2.62E-08	4.39E-09	1.34E-09	2.95E-07	5.26E-08
	Ku	4.14E-11	1.57E-10	2.68E-12	7.39E-11	1.05E-09

Table 4.32: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 0.5m depth (Faculty of Education Area)



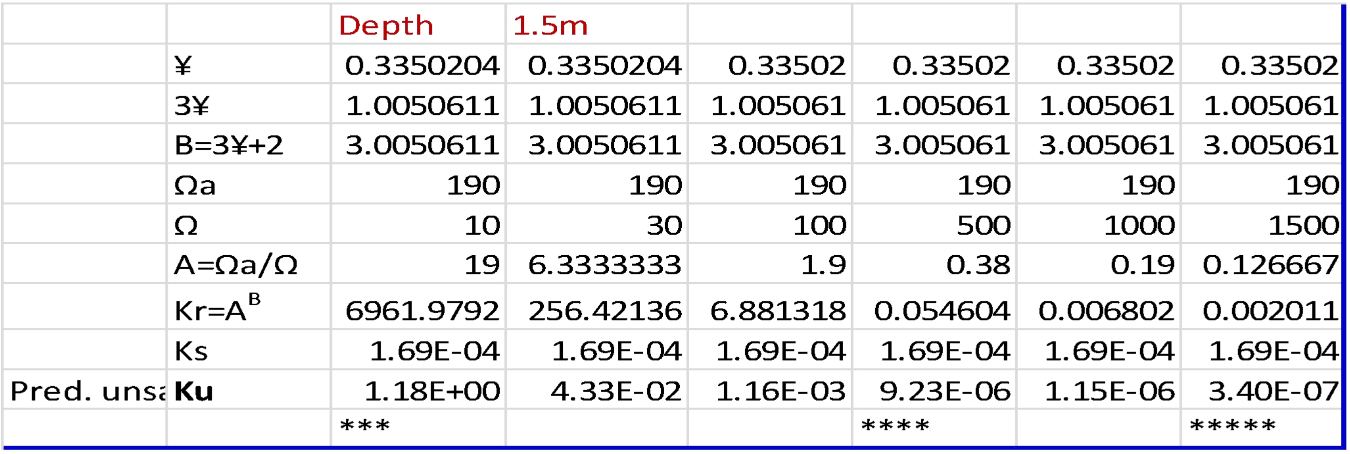
PREDICTION OF UNSATURATED HYDRAULIC CONDUCTIVITY (Ku)FOR BROOKCOREY							
	Depth	0.5m					
	¥	0.3172586	0.3172586	0.3172586	0.3172586	0.3172586	0.3172586
	3¥	0.9517757	0.9517757	0.9517757	0.9517757	0.9517757	0.9517757
	B=3¥+2	2.9517757	2.9517757	2.9517757	2.9517757	2.9517757	2.9517757
	Ωa	240	240	240	240	240	240
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	24	8	2.4	0.48	0.24	0.16
	$Kr=A^B$	11859.709	463.14725	13.252515	0.1145765	0.0148089	0.0044745
	Ks	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
Pred. unsat. H.C.	**Ku**	1.71E+00	6.67E-02	1.91E-03	1.65E-05	2.13E-06	6.44E-07
		***			****		*****

Table 4.33: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 1.0m depth (Faculty of Education Area)



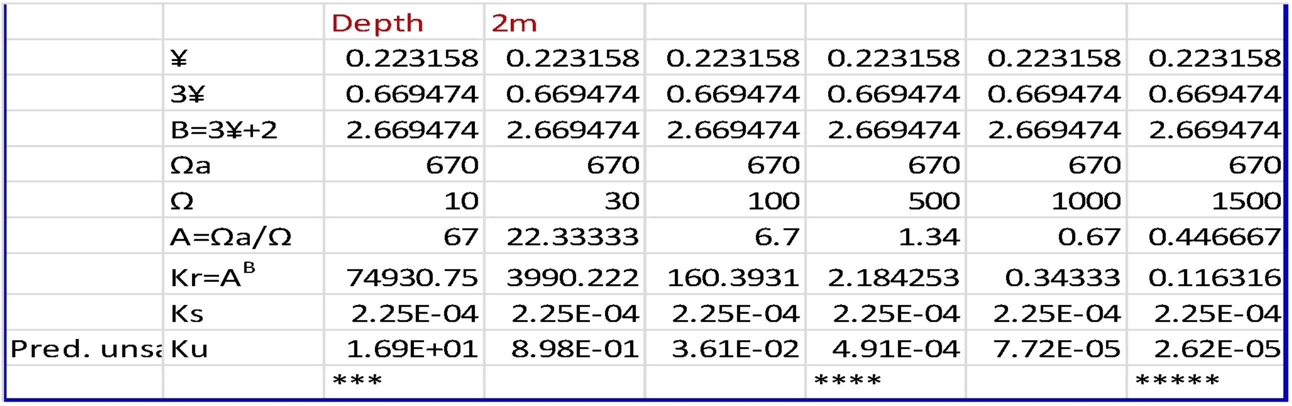
		Depth	1m				
	¥	1.1077843	1.1077843	1.1077843	1.107784313	1.107784313	1.107784313
	3¥	3.3233529	3.3233529	3.3233529	3.32335294	3.32335294	3.32335294
	B=3¥+2	5.3233529	5.3233529	5.3233529	5.32335294	5.32335294	5.32335294
	Ωa	43	43	43	43	43	43
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	4.3	1.4333333	0.43	0.086	0.043	0.028666667
	$Kr=A^B$	2356.0048	6.7965941	0.0111898	2.12794E-06	5.3146E-08	6.13867E-09
	Ks	5.63E-04	5.63E-04	5.63E-04	5.63E-04	5.63E-04	5.63E-04
Pred. uns	**Ku**	1.33E+00	3.83E-03	6.30E-06	1.20E-09	2.99E-11	3.46E-12
		***			****		*****

Table 4.34: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 1.5m depth (Faculty of Education Area)



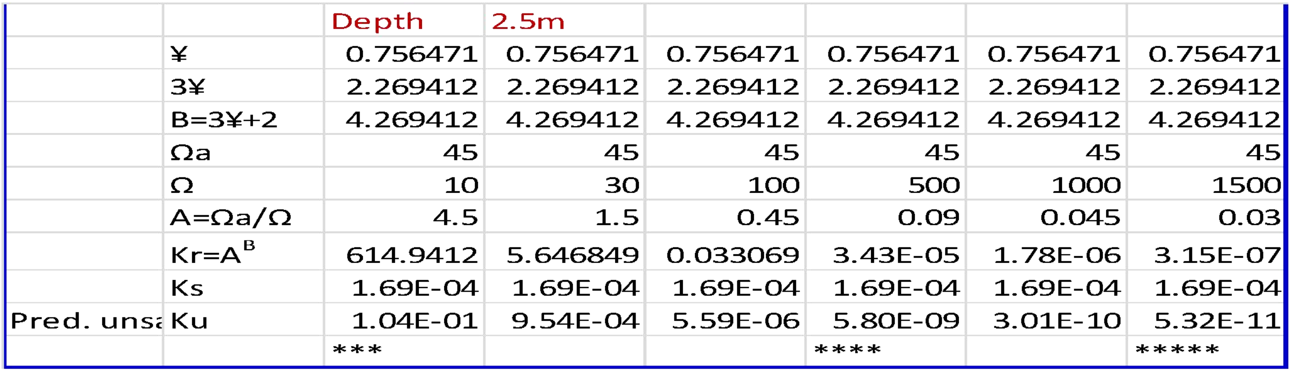
		Depth	1.5m				
	¥	0.3350204	0.3350204	0.33502	0.33502	0.33502	0.33502
	3¥	1.0050611	1.0050611	1.005061	1.005061	1.005061	1.005061
	B=3¥+2	3.0050611	3.0050611	3.005061	3.005061	3.005061	3.005061
	Ωa	190	190	190	190	190	190
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	19	6.3333333	1.9	0.38	0.19	0.126667
	$Kr=A^B$	6961.9792	256.42136	6.881318	0.054604	0.006802	0.002011
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Pred. uns	**Ku**	1.18E+00	4.33E-02	1.16E-03	9.23E-06	1.15E-06	3.40E-07
		***			****		*****

Table 4.35: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 2.0m depth (Faculty of Education Area)



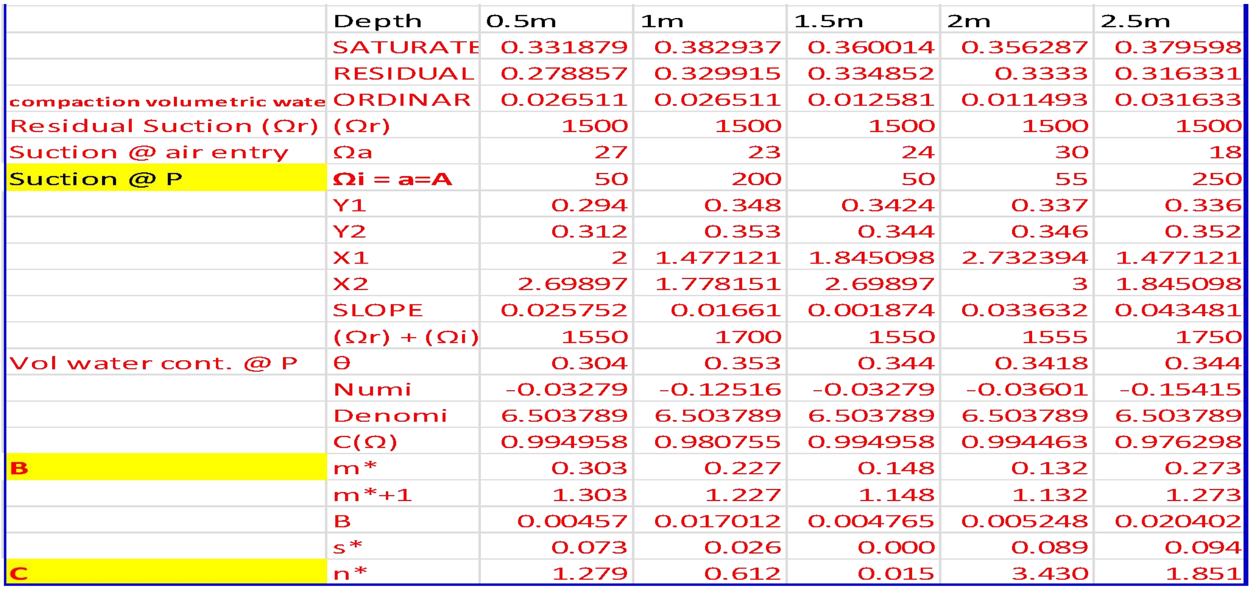
		Depth	2m				
	¥	0.223158	0.223158	0.223158	0.223158	0.223158	0.223158
	3¥	0.669474	0.669474	0.669474	0.669474	0.669474	0.669474
	B=3¥+2	2.669474	2.669474	2.669474	2.669474	2.669474	2.669474
	Ωa	670	670	670	670	670	670
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	67	22.33333	6.7	1.34	0.67	0.446667
	$Kr=A^B$	74930.75	3990.222	160.3931	2.184253	0.34333	0.116316
	Ks	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04
Pred. unsa	Ku	1.69E+01	8.98E-01	3.61E-02	4.91E-04	7.72E-05	2.62E-05
		***			****		*****

Table 4.36: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 2.5m depth (Faculty of Education Area)



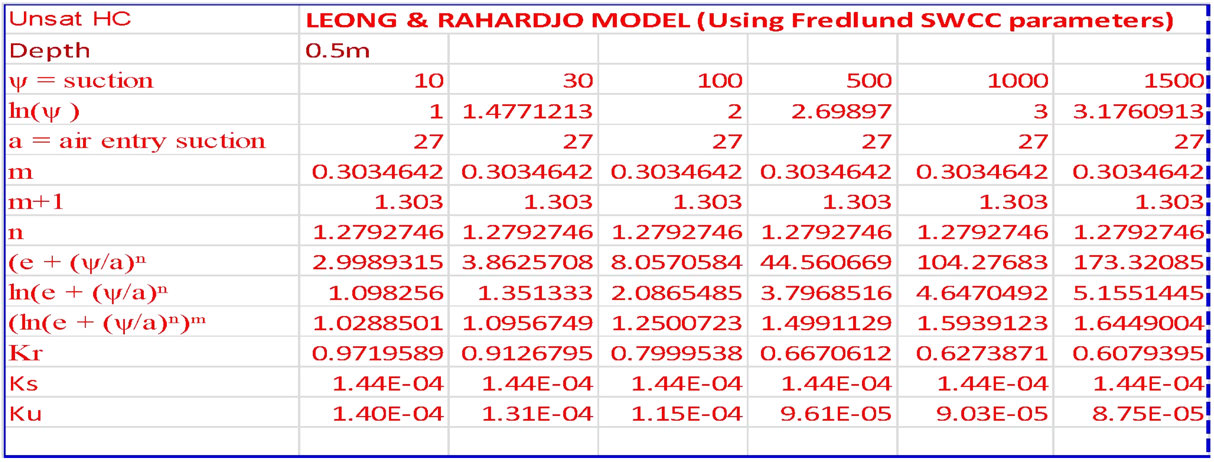
		Depth	2.5m				
	¥	0.756471	0.756471	0.756471	0.756471	0.756471	0.756471
	3¥	2.269412	2.269412	2.269412	2.269412	2.269412	2.269412
	B=3¥+2	4.269412	4.269412	4.269412	4.269412	4.269412	4.269412
	Ωa	45	45	45	45	45	45
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	4.5	1.5	0.45	0.09	0.045	0.03
	$Kr=A^B$	614.9412	5.646849	0.033069	3.43E-05	1.78E-06	3.15E-07
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Pred. unsa	Ku	1.04E-01	9.54E-04	5.59E-06	5.80E-09	3.01E-10	5.32E-11
		***			****		*****

Table 4.37: Fredlund and Xing Model using SWCC parameters (Faculty of Education)



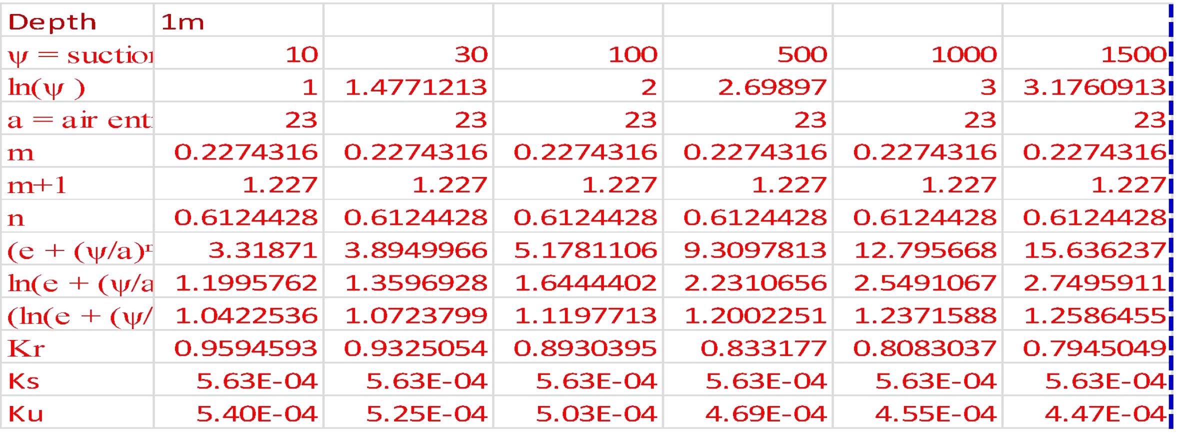
	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATE	0.331879	0.382937	0.360014	0.356287	0.379598
	RESIDUAL	0.278857	0.329915	0.334852	0.3333	0.316331
compaction volumetric wate	ORDINAR	0.026511	0.026511	0.012581	0.011493	0.031633
Residual Suction (Ωr)	(Ωr)	1500	1500	1500	1500	1500
Suction @ air entry	Ωa	27	23	24	30	18
Suction @ P	**Ωi = a=A**	50	200	50	55	250
	Y1	0.294	0.348	0.3424	0.337	0.336
	Y2	0.312	0.353	0.344	0.346	0.352
	X1	2	1.477121	1.845098	2.732394	1.477121
	X2	2.69897	1.778151	2.69897	3	1.845098
	SLOPE	0.025752	0.01661	0.001874	0.033632	0.043481
	(Ωr) + (Ωi)	1550	1700	1550	1555	1750
Vol water cont. @ P	θ	0.304	0.353	0.344	0.3418	0.344
	Numi	-0.03279	-0.12516	-0.03279	-0.03601	-0.15415
	Denomi	6.503789	6.503789	6.503789	6.503789	6.503789
	C(Ω)	0.994958	0.980755	0.994958	0.994463	0.976298
B	m*	0.303	0.227	0.148	0.132	0.273
	m*+1	1.303	1.227	1.148	1.132	1.273
	B	0.00457	0.017012	0.004765	0.005248	0.020402
	s*	0.073	0.026	0.000	0.089	0.094
C	n*	1.279	0.612	0.015	3.430	1.851

Table 4.38: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 0.5m depth (Faculty of Education Area)



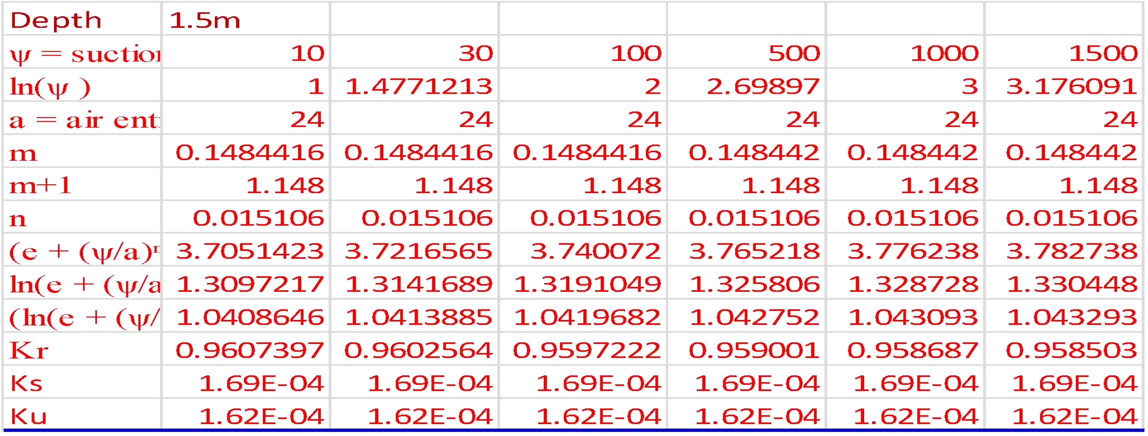
Unsat HC	LEONG & RAHARDJO MODEL (Using Fredlund SWCC parameters)					
Depth	0.5m					
ψ = suction	10	30	100	500	1000	1500
$\ln(\psi)$	1	1.4771213	2	2.69897	3	3.1760913
a = air entry suction	27	27	27	27	27	27
m	0.3034642	0.3034642	0.3034642	0.3034642	0.3034642	0.3034642
m+1	1.303	1.303	1.303	1.303	1.303	1.303
n	1.2792746	1.2792746	1.2792746	1.2792746	1.2792746	1.2792746
$(e + (\psi/a)^n$	2.9989315	3.8625708	8.0570584	44.560669	104.27683	173.32085
$\ln(e + (\psi/a)^n$	1.098256	1.351333	2.0865485	3.7968516	4.6470492	5.1551445
$(\ln(e + (\psi/a)^n)^m$	1.0288501	1.0956749	1.2500723	1.4991129	1.5939123	1.6449004
Kr	0.9719589	0.9126795	0.7999538	0.6670612	0.6273871	0.6079395
Ks	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04	1.44E-04
Ku	1.40E-04	1.31E-04	1.15E-04	9.61E-05	9.03E-05	8.75E-05

Table 4.39: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 1.0m depth (Faculty of Education Area)



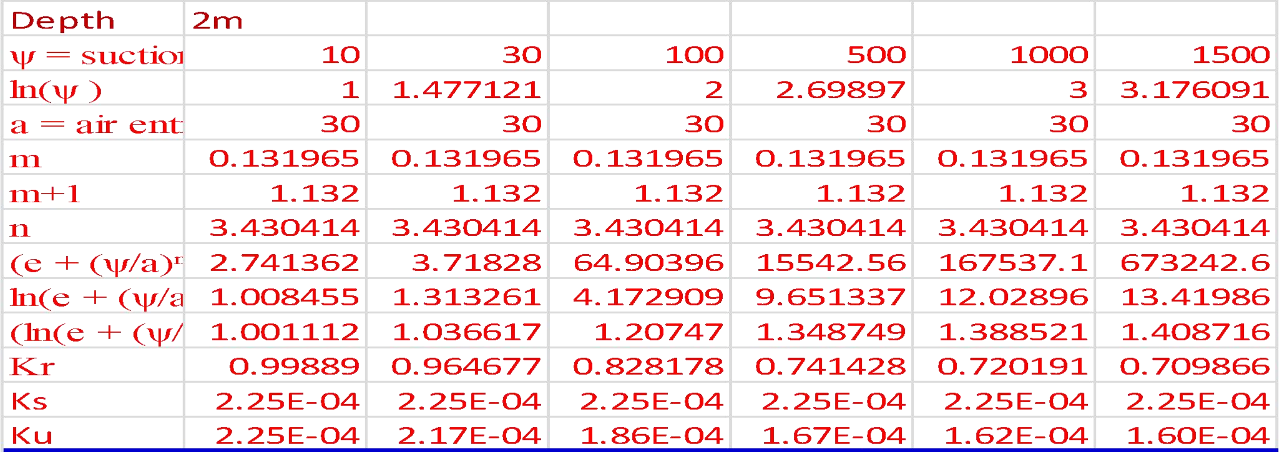
Depth	1m					
ψ = suctio	10	30	100	500	1000	1500
$\ln(\psi)$	1	1.4771213	2	2.69897	3	3.1760913
a = air ent	23	23	23	23	23	23
m	0.2274316	0.2274316	0.2274316	0.2274316	0.2274316	0.2274316
m+1	1.227	1.227	1.227	1.227	1.227	1.227
n	0.6124428	0.6124428	0.6124428	0.6124428	0.6124428	0.6124428
$(e + (\psi/a)$	3.31871	3.8949966	5.1781106	9.3097813	12.795668	15.636237
$\ln(e + (\psi/a$	1.1995762	1.3596928	1.6444402	2.2310656	2.5491067	2.7495911
$(\ln(e + (\psi/$	1.0422536	1.0723799	1.1197713	1.2002251	1.2371588	1.2586455
Kr	0.9594593	0.9325054	0.8930395	0.833177	0.8083037	0.7945049
Ks	5.63E-04	5.63E-04	5.63E-04	5.63E-04	5.63E-04	5.63E-04
Ku	5.40E-04	5.25E-04	5.03E-04	4.69E-04	4.55E-04	4.47E-04

Table 4.40: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 1.5m depth (Faculty of Education Area)



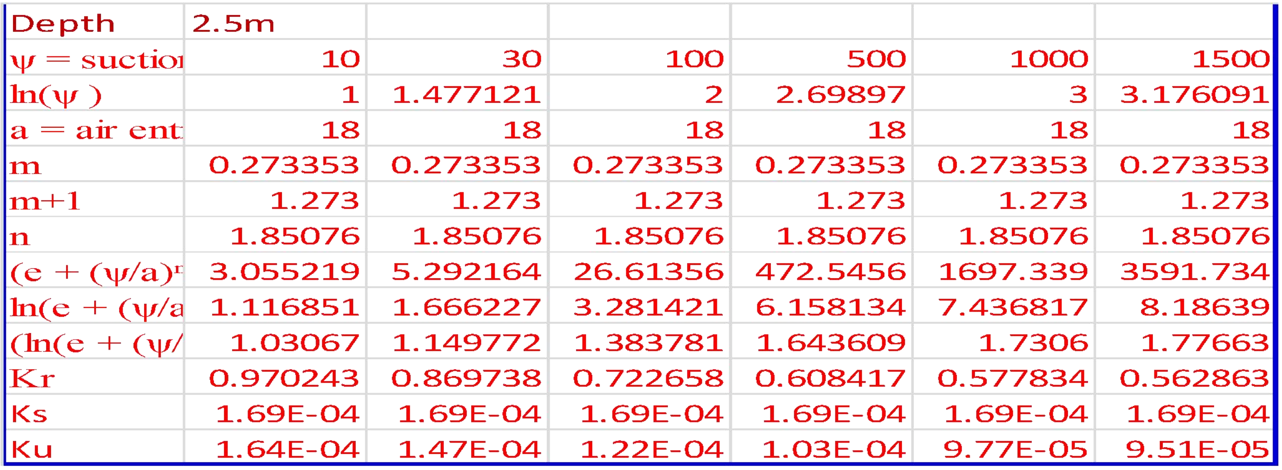
Depth	1.5m					
ψ = suctio	10	30	100	500	1000	1500
$\ln(\psi)$	1	1.4771213	2	2.69897	3	3.176091
a = air ent	24	24	24	24	24	24
m	0.1484416	0.1484416	0.1484416	0.148442	0.148442	0.148442
m+1	1.148	1.148	1.148	1.148	1.148	1.148
n	0.015106	0.015106	0.015106	0.015106	0.015106	0.015106
$(e + (\psi/a)$	3.7051423	3.7216565	3.740072	3.765218	3.776238	3.782738
$\ln(e + (\psi/a$	1.3097217	1.3141689	1.3191049	1.325806	1.328728	1.330448
$(\ln(e + (\psi/$	1.0408646	1.0413885	1.0419682	1.042752	1.043093	1.043293
Kr	0.9607397	0.9602564	0.9597222	0.959001	0.958687	0.958503
Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Ku	1.62E-04	1.62E-04	1.62E-04	1.62E-04	1.62E-04	1.62E-04

Table 4.41: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 2.0m depth (Faculty of Education Area)



Depth	2m					
ψ = suctio	10	30	100	500	1000	1500
ln(ψ)	1	1.477121	2	2.69897	3	3.176091
a = air ent	30	30	30	30	30	30
m	0.131965	0.131965	0.131965	0.131965	0.131965	0.131965
m+1	1.132	1.132	1.132	1.132	1.132	1.132
n	3.430414	3.430414	3.430414	3.430414	3.430414	3.430414
(e + (ψ/a)^{n}	2.741362	3.71828	64.90396	15542.56	167537.1	673242.6
ln(e + (ψ/a	1.008455	1.313261	4.172909	9.651337	12.02896	13.41986
(ln(e + (ψ/	1.001112	1.036617	1.20747	1.348749	1.388521	1.408716
Kr	0.99889	0.964677	0.828178	0.741428	0.720191	0.709866
Ks	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04	2.25E-04
Ku	2.25E-04	2.17E-04	1.86E-04	1.67E-04	1.62E-04	1.60E-04

Table 4.42: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 2.5m depth (Faculty of Education Area)

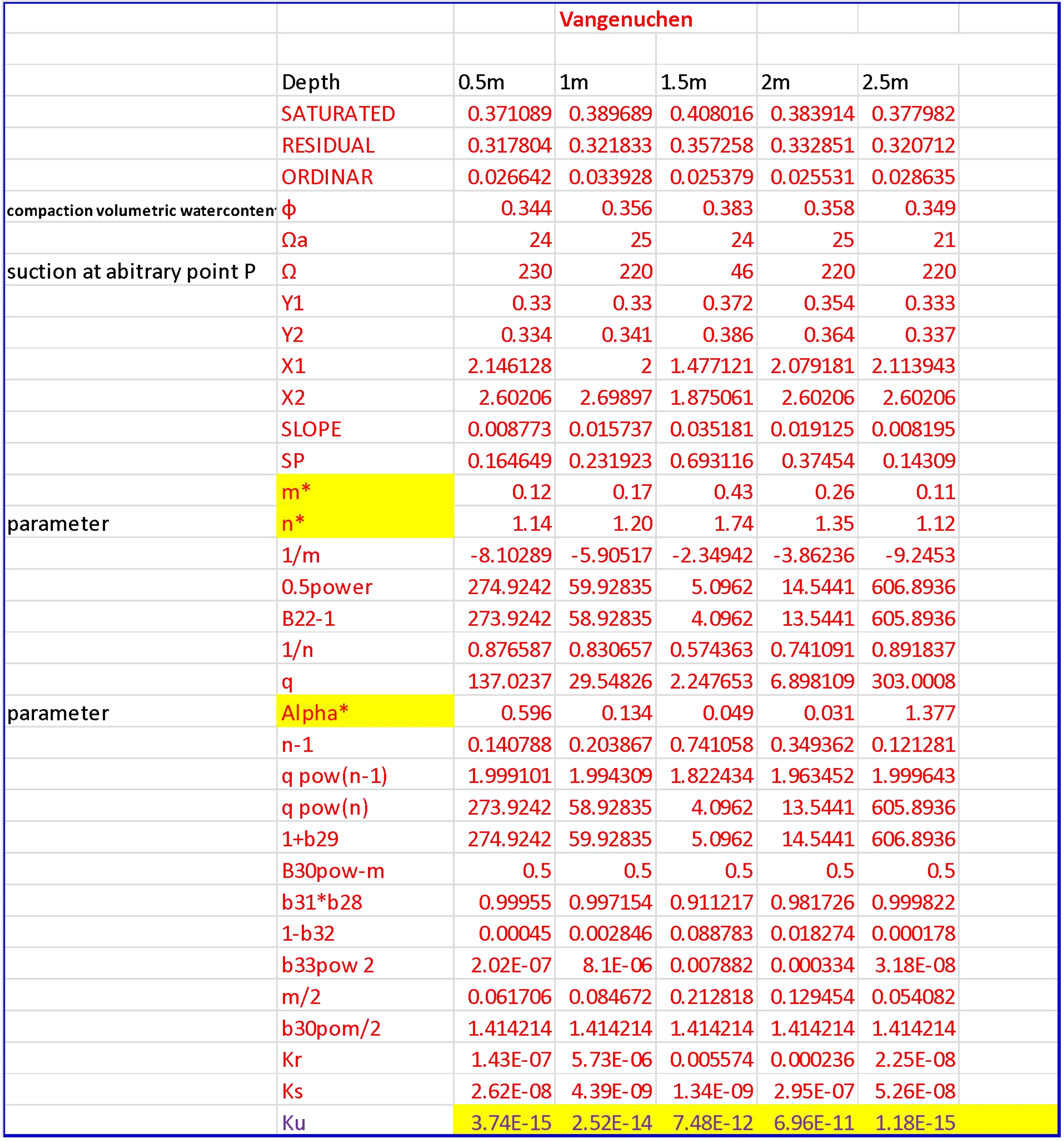


Depth	2.5m					
ψ = suctio	10	30	100	500	1000	1500
ln(ψ)	1	1.477121	2	2.69897	3	3.176091
a = air ent	18	18	18	18	18	18
m	0.273353	0.273353	0.273353	0.273353	0.273353	0.273353
m+1	1.273	1.273	1.273	1.273	1.273	1.273
n	1.85076	1.85076	1.85076	1.85076	1.85076	1.85076
(e + (ψ/a)^{n}	3.055219	5.292164	26.61356	472.5456	1697.339	3591.734
ln(e + (ψ/a	1.116851	1.666227	3.281421	6.158134	7.436817	8.18639
(ln(e + (ψ/	1.03067	1.149772	1.383781	1.643609	1.7306	1.77663
Kr	0.970243	0.869738	0.722658	0.608417	0.577834	0.562863
Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Ku	1.64E-04	1.47E-04	1.22E-04	1.03E-04	9.77E-05	9.51E-05

Similarly, the same procedure of obtaining hydraulic conductivity for basement and education was repeated for the faculty of environmental location.

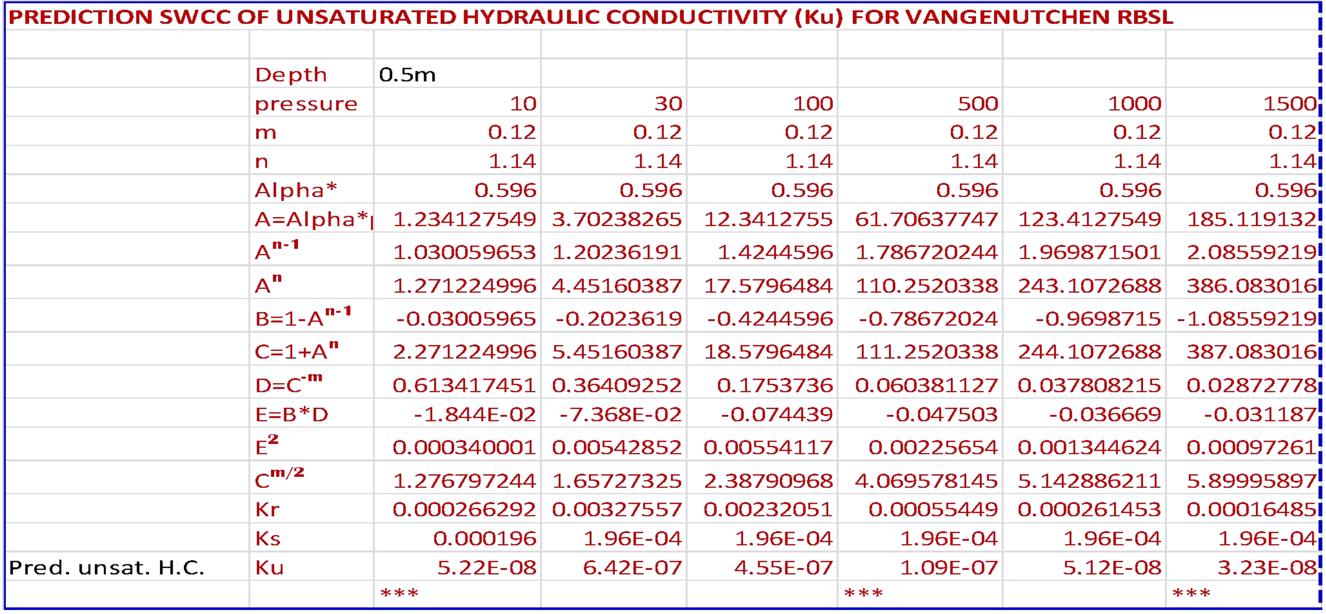
PREDICTION OF HYDRAULIC CONDUCTIVITY USING (VAN-GENUTCHEN, BROOK-COREY AND FREDLUND AND XING MODELS) FOR FACULTY OF ENVIRONMENTAL SCIENCES AREA)

Table 4.43: Vangenutchen model using SWCC parameters (Faculty of Environmental Sciences area)



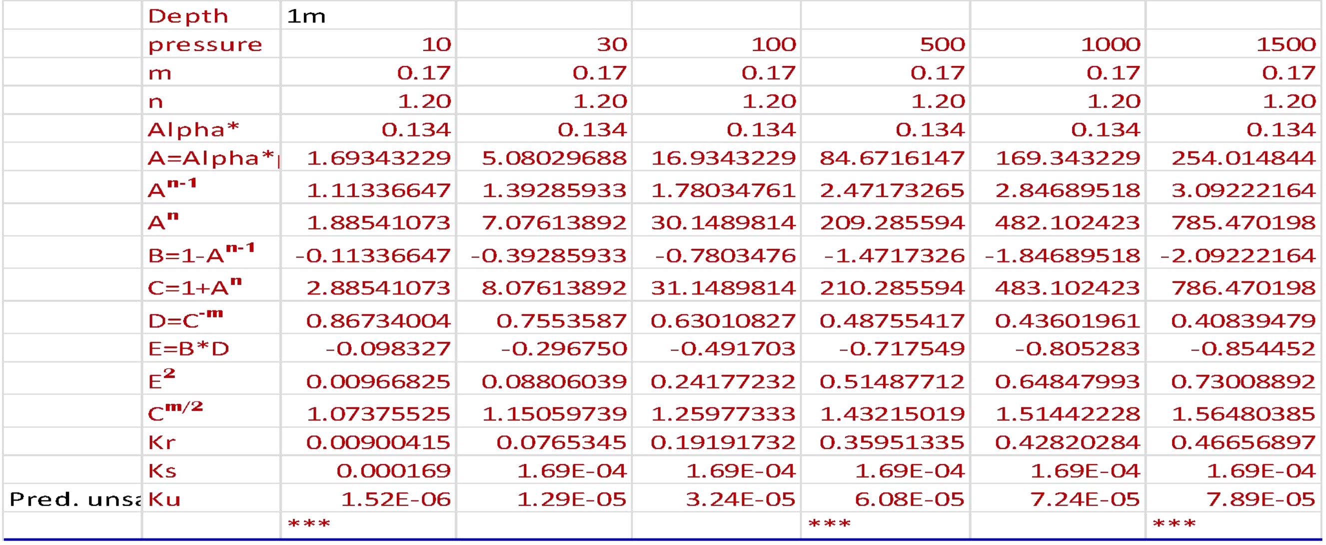
			Vangenuchen			
	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATED	0.371089	0.389689	0.408016	0.383914	0.377982
	RESIDUAL	0.317804	0.321833	0.357258	0.332851	0.320712
	ORDINAR	0.026642	0.033928	0.025379	0.025531	0.028635
compaction volumetric waterconten	ϕ	0.344	0.356	0.383	0.358	0.349
	Ωa	24	25	24	25	21
suction at abitrary point P	Ω	230	220	46	220	220
	Y1	0.33	0.33	0.372	0.354	0.333
	Y2	0.334	0.341	0.386	0.364	0.337
	X1	2.146128	2	1.477121	2.079181	2.113943
	X2	2.60206	2.69897	1.875061	2.60206	2.60206
	SLOPE	0.008773	0.015737	0.035181	0.019125	0.008195
	SP	0.164649	0.231923	0.693116	0.37454	0.14309
	m*	0.12	0.17	0.43	0.26	0.11
parameter	n*	1.14	1.20	1.74	1.35	1.12
	1/m	-8.10289	-5.90517	-2.34942	-3.86236	-9.2453
	0.5power	274.9242	59.92835	5.0962	14.5441	606.8936
	B22-1	273.9242	58.92835	4.0962	13.5441	605.8936
	1/n	0.876587	0.830657	0.574363	0.741091	0.891837
	q	137.0237	29.54826	2.247653	6.898109	303.0008
parameter	Alpha*	0.596	0.134	0.049	0.031	1.377
	n-1	0.140788	0.203867	0.741058	0.349362	0.121281
	q pow(n-1)	1.999101	1.994309	1.822434	1.963452	1.999643
	q pow(n)	273.9242	58.92835	4.0962	13.5441	605.8936
	1+b29	274.9242	59.92835	5.0962	14.5441	606.8936
	B30pow-m	0.5	0.5	0.5	0.5	0.5
	b31*b28	0.99955	0.997154	0.911217	0.981726	0.999822
	1-b32	0.00045	0.002846	0.088783	0.018274	0.000178
	b33pow 2	2.02E-07	8.1E-06	0.007882	0.000334	3.18E-08
	m/2	0.061706	0.084672	0.212818	0.129454	0.054082
	b30pom/2	1.414214	1.414214	1.414214	1.414214	1.414214
	Kr	1.43E-07	5.73E-06	0.005574	0.000236	2.25E-08
	Ks	2.62E-08	4.39E-09	1.34E-09	2.95E-07	5.26E-08
	Ku	3.74E-15	2.52E-14	7.48E-12	6.96E-11	1.18E-15

Table 4.44: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 0.5m depth (Faculty of Environmental Sciences area)



PREDICTION SWCC OF UNSATURATED HYDRAULIC CONDUCTIVITY (Ku) FOR VANGENUTCHEN RBSL							
	Depth	0.5m					
	pressure	10	30	100	500	1000	1500
	m	0.12	0.12	0.12	0.12	0.12	0.12
	n	1.14	1.14	1.14	1.14	1.14	1.14
	Alpha*	0.596	0.596	0.596	0.596	0.596	0.596
	A=Alpha*	1.234127549	3.70238265	12.3412755	61.70637747	123.4127549	185.119132
	A^{n-1}	1.030059653	1.20236191	1.4244596	1.786720244	1.969871501	2.08559219
	A^{n}	1.271224996	4.45160387	17.5796484	110.2520338	243.1072688	386.083016
	$B=1-A^{n-1}$	-0.03005965	-0.2023619	-0.4244596	-0.78672024	-0.9698715	-1.08559219
	$C=1+A^{n}$	2.271224996	5.45160387	18.5796484	111.2520338	244.1072688	387.083016
	$D=C^{-m}$	0.613417451	0.36409252	0.1753736	0.060381127	0.037808215	0.02872778
	E=B*D	-1.844E-02	-7.368E-02	-0.074439	-0.047503	-0.036669	-0.031187
	E^{2}	0.000340001	0.00542852	0.00554117	0.00225654	0.001344624	0.00097261
	$C^{m/2}$	1.276797244	1.65727325	2.38790968	4.069578145	5.142886211	5.89995897
	Kr	0.000266292	0.00327557	0.00232051	0.00055449	0.000261453	0.00016485
	Ks	0.000196	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Pred. unsat. H.C.	Ku	5.22E-08	6.42E-07	4.55E-07	1.09E-07	5.12E-08	3.23E-08
		***			***		***

Table 4.45: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 1.0m depth (Faculty of Environmental Sciences area)



	Depth	1m					
	pressure	10	30	100	500	1000	1500
	m	0.17	0.17	0.17	0.17	0.17	0.17
	n	1.20	1.20	1.20	1.20	1.20	1.20
	Alpha*	0.134	0.134	0.134	0.134	0.134	0.134
	A=Alpha*	1.69343229	5.08029688	16.9343229	84.6716147	169.343229	254.014844
	A^{n-1}	1.11336647	1.39285933	1.78034761	2.47173265	2.84689518	3.09222164
	A^{n}	1.88541073	7.07613892	30.1489814	209.285594	482.102423	785.470198
	$B=1-A^{n-1}$	-0.11336647	-0.39285933	-0.7803476	-1.4717326	-1.84689518	-2.09222164
	$C=1+A^{n}$	2.88541073	8.07613892	31.1489814	210.285594	483.102423	786.470198
	$D=C^{-m}$	0.86734004	0.7553587	0.63010827	0.48755417	0.43601961	0.40839479
	E=B*D	-0.098327	-0.296750	-0.491703	-0.717549	-0.805283	-0.854452
	E^{2}	0.00966825	0.08806039	0.24177232	0.51487712	0.64847993	0.73008892
	$C^{m/2}$	1.07375525	1.15059739	1.25977333	1.43215019	1.51442228	1.56480385
	Kr	0.00900415	0.0765345	0.19191732	0.35951335	0.42820284	0.46656897
	Ks	0.000169	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
Pred. unsa	Ku	1.52E-06	1.29E-05	3.24E-05	6.08E-05	7.24E-05	7.89E-05
		***			***		***

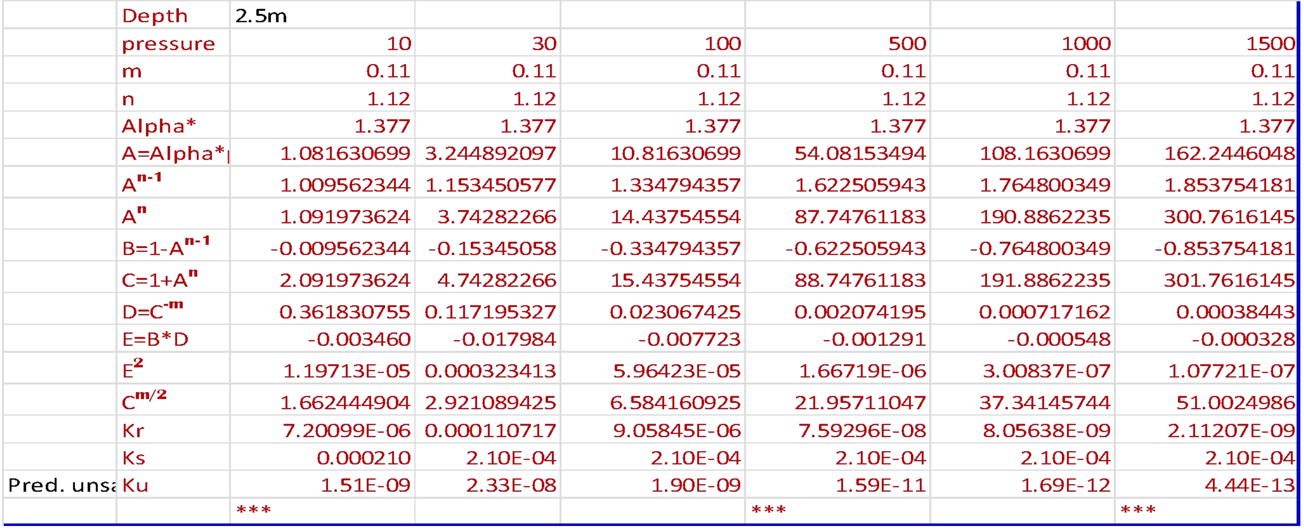
Table 4.46: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 1.5m depth (Faculty of Environmental Sciences area)

	Depth	1.5m					
	pressure	10	30	100	500	1000	1500
	m	0.43	0.43	0.43	0.43	0.43	0.43
	n	1.74	1.74	1.74	1.74	1.74	1.74
	Alpha*	0.049	0.049	0.049	0.049	0.049	0.049
	A=Alpha*	4.25636625	12.7690987	42.56366246	212.8183123	425.6366246	638.4549369
	A^{n-1}	2.92519237	6.60281297	16.11433986	53.11166223	88.77089666	119.8848925
	A^{n}	12.45069	84.3119708	685.8853227	11303.13432	37784.14482	76541.1015
	$B=1-A^{n-1}$	-1.9251924	-5.602813	-15.11433986	-52.11166223	-87.77089666	-118.884893
	$C=1+A^{n}$	13.45069	85.3119708	686.8853227	11304.13432	37785.14482	76542.1015
	$D=C^{-m}$	0.88073905	0.80472397	0.726748407	0.633797633	0.597506752	0.577248392
	E=B*D	-1.695592	-4.508718	-10.984322	-33.028248	-52.443703	-68.626113
	E^{2}	2.87503257	20.3285373	120.6553389	1090.865177	2750.342025	4709.543397
	$C^{m/2}$	1.06555623	1.11474756	1.173026858	1.256101383	1.293685145	1.316190143
	Kr	2.6981519	18.2360008	102.8581214	868.4531295	2125.974806	3578.1634
	Ks	0.000196	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Pred. unsa	Ku	5.29E-04	3.57E-03	2.02E-02	1.70E-01	4.17E-01	7.01E-01
		***			***		***

Table 4.47: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 2.0m depth (Faculty of Environmental Sciences area)

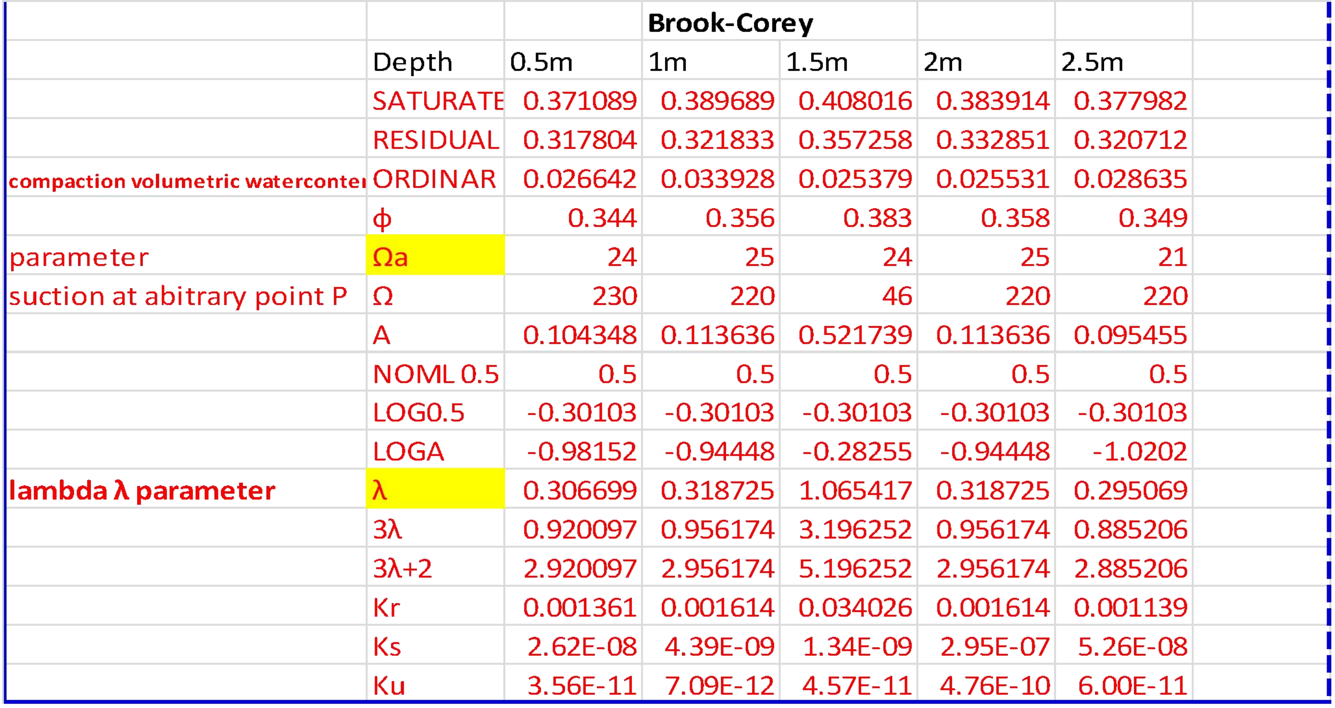
	Depth	2m					
	pressure	10	30	100	500	1000	1500
	m	0.26	0.26	0.26	0.26	0.26	0.26
	n	1.35	1.35	1.35	1.35	1.35	1.35
	Alpha*	0.031	0.031	0.031	0.031	0.031	0.031
	A=Alpha*	2.58908894	7.767266831	25.89088944	129.4544472	258.9088944	388.3633416
	A^{n-1}	1.39424069	2.046565627	3.116732397	5.468810911	6.967248122	8.027509528
	A^{n}	3.60981316	15.89622131	80.6949739	707.9618933	1803.882508	3117.590425
	$B=1-A^{n-1}$	-0.39424069	-1.04656563	-2.1167324	-4.468810911	-5.96724812	-7.02750953
	$C=1+A^{n}$	4.60981316	16.89622131	81.6949739	708.9618933	1804.882508	3118.590425
	$D=C^{-m}$	0.95321349	0.915171752	0.871049902	0.813989123	0.790485502	0.777046112
	E=B*D	-0.375796	-0.957787	-1.843780	-3.637563	-4.717023	-5.460699
	E^{2}	0.14122229	0.917356509	3.399523017	13.23186802	22.25030718	29.8192331
	$C^{m/2}$	1.02424749	1.045318645	1.071466216	1.108385152	1.124742344	1.13442713
	Kr	0.13787907	0.877585523	3.172776675	11.93796939	19.78258159	26.2857193
	Ks	0.000196	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Pred. unsa	Ku	2.70E-05	1.72E-04	6.22E-04	2.34E-03	3.88E-03	5.15E-03
		***			***		***

Table 4.48: Prediction of unsaturated hydraulic conductivity (Ku) using Vangenutchen model for 2.5m depth (Faculty of Environmental Sciences area)



	Depth	2.5m					
	pressure	10	30	100	500	1000	1500
	m	0.11	0.11	0.11	0.11	0.11	0.11
	n	1.12	1.12	1.12	1.12	1.12	1.12
	Alpha*	1.377	1.377	1.377	1.377	1.377	1.377
	A=Alpha*	1.081630699	3.244892097	10.81630699	54.08153494	108.1630699	162.2446048
	A^{n-1}	1.009562344	1.153450577	1.334794357	1.622505943	1.764800349	1.853754181
	A^{n}	1.091973624	3.74282266	14.43754554	87.74761183	190.8862235	300.7616145
	$B=1-A^{n-1}$	-0.009562344	-0.15345058	-0.334794357	-0.622505943	-0.764800349	-0.853754181
	$C=1+A^{n}$	2.091973624	4.74282266	15.43754554	88.74761183	191.8862235	301.7616145
	$D=C^{-m}$	0.361830755	0.117195327	0.023067425	0.002074195	0.000717162	0.00038443
	E=B*D	-0.003460	-0.017984	-0.007723	-0.001291	-0.000548	-0.000328
	E^{2}	1.19713E-05	0.000323413	5.96423E-05	1.66719E-06	3.00837E-07	1.07721E-07
	$C^{m/2}$	1.662444904	2.921089425	6.584160925	21.95711047	37.34145744	51.0024986
	Kr	7.20099E-06	0.000110717	9.05845E-06	7.59296E-08	8.05638E-09	2.11207E-09
	Ks	0.000210	2.10E-04	2.10E-04	2.10E-04	2.10E-04	2.10E-04
Pred. unsa	Ku	1.51E-09	2.33E-08	1.90E-09	1.59E-11	1.69E-12	4.44E-13
		***			***		***

Table 4.49: Brook-Corey model using SWCC parameters (Faculty of Environmental Sciences area)



			Brook-Corey				
	Depth	0.5m	1m	1.5m	2m	2.5m	
	SATURATE	0.371089	0.389689	0.408016	0.383914	0.377982	
	RESIDUAL	0.317804	0.321833	0.357258	0.332851	0.320712	
compaction volumetric watercontei	ORDINAR	0.026642	0.033928	0.025379	0.025531	0.028635	
	ϕ	0.344	0.356	0.383	0.358	0.349	
parameter	Ωa	24	25	24	25	21	
suction at abitrary point P	Ω	230	220	46	220	220	
	A	0.104348	0.113636	0.521739	0.113636	0.095455	
	NOML 0.5	0.5	0.5	0.5	0.5	0.5	
	LOG0.5	-0.30103	-0.30103	-0.30103	-0.30103	-0.30103	
	LOGA	-0.98152	-0.94448	-0.28255	-0.94448	-1.0202	
lambda λ parameter	λ	0.306699	0.318725	1.065417	0.318725	0.295069	
	3λ	0.920097	0.956174	3.196252	0.956174	0.885206	
	3λ+2	2.920097	2.956174	5.196252	2.956174	2.885206	
	Kr	0.001361	0.001614	0.034026	0.001614	0.001139	
	Ks	2.62E-08	4.39E-09	1.34E-09	2.95E-07	5.26E-08	
	Ku	3.56E-11	7.09E-12	4.57E-11	4.76E-10	6.00E-11	

Table 4.50: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 0.5m depth (Faculty of Environmental Sciences area)

PREDICTION OF UNSATURATED HYDRAULIC CONDUCTIVITY (Ku)FOR BROOKCOREY							
	Depth	0.5m					
	¥	0.306699	0.306699	0.306699	0.306699	0.306699	0.306699
	3¥	0.920097	0.920097	0.920097	0.920097	0.920097	0.920097
	B=3¥+2	2.920097	2.920097	2.920097	2.920097	2.920097	2.920097
	Ωa	24	24	24	24	24	24
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	2.4	0.8	0.24	0.048	0.024	0.016
	$Kr=A^B$	12.89002	0.521211	0.015494	0.000141	1.86E-05	5.7E-06
	Ks	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Pred. unsat. H.C.	**Ku**	2.53E-03	1.02E-04	3.04E-06	2.76E-08	3.65E-09	1.12E-09
		***			****		*****

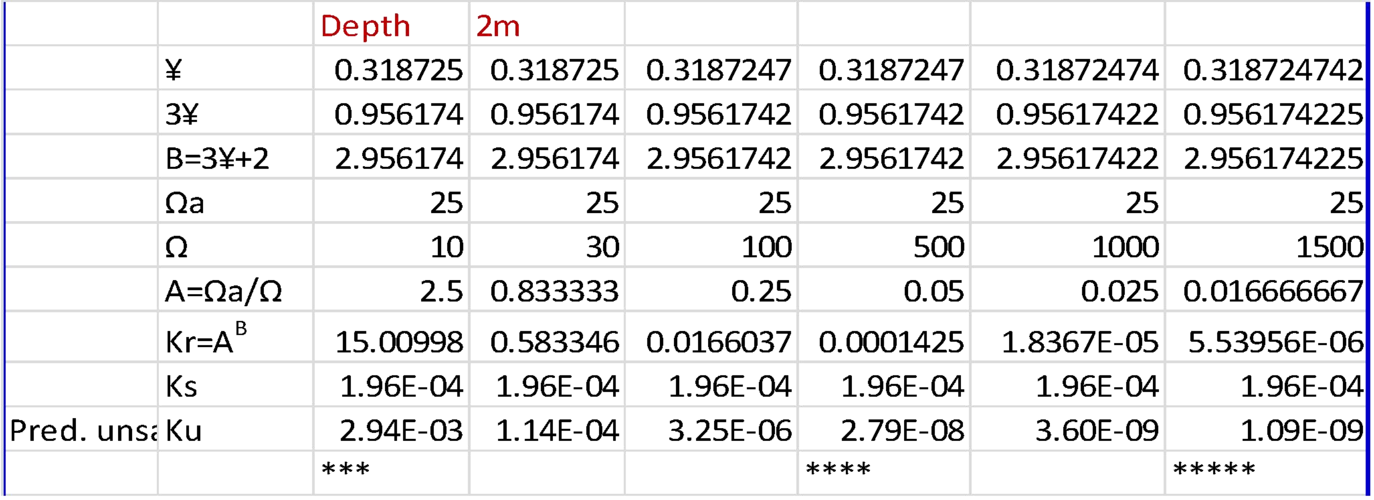
Table 4.51: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 1.0m depth (Faculty of Environmental Sciences area)

		Depth	1m						
	¥	0.318725	0.318725	0.318725	0.318725	0.318725	0.318725		¥
	3¥	0.956174	0.956174	0.956174	0.956174	0.956174	0.956174		3¥
	B=3¥+2	2.956174	2.956174	2.956174	2.956174	2.956174	2.956174		B=3¥+2
	Ωa	25	25	25	25	25	25		Ωa
	Ω	10	30	100	500	1000	1500		Ω
	A=Ωa/Ω	2.5	0.833333	0.25	0.05	0.025	0.016667		A=Ωa/Ω
	$Kr=A^B$	15.00998	0.583346	0.016604	0.000143	1.84E-05	5.54E-06		$Kr=A^B$
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04		Ks
Pred. unsa	**Ku**	2.54E-03	9.86E-05	2.81E-06	2.41E-08	3.10E-09	9.36E-10	Pred. unsa	**Ku**
		***			****		*****		

Table 4.52: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 1.5m depth (Faculty of Environmental Sciences area)

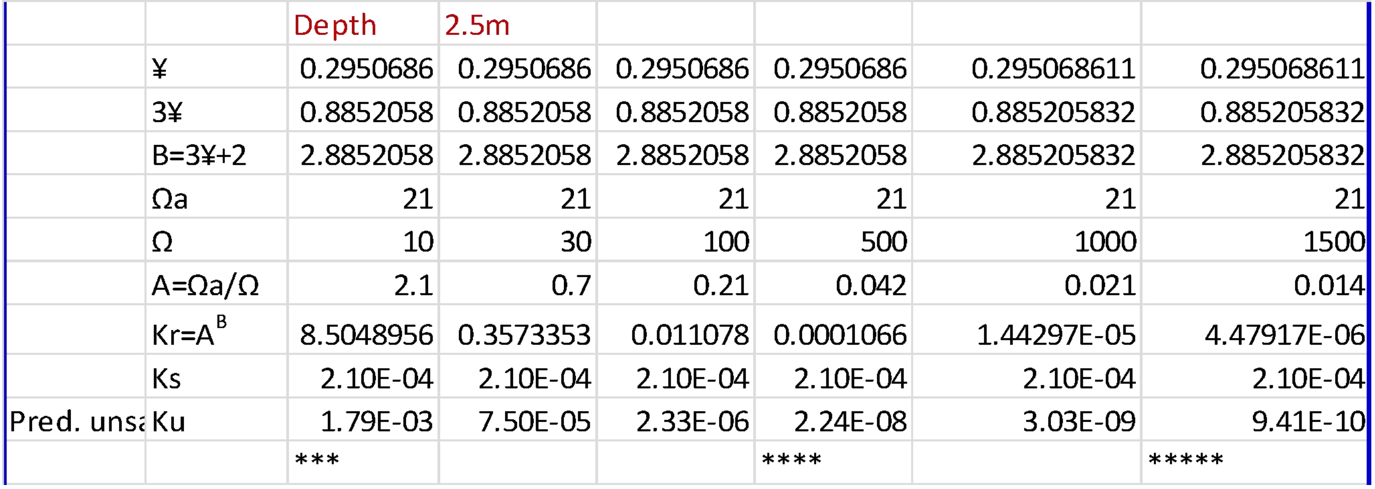
		Depth	1.5m				
	¥	1.065417	1.065417	1.065417	1.065417	1.065417	1.065417
	3¥	3.196252	3.196252	3.196252	3.196252	3.196252	3.196252
	B=3¥+2	5.196252	5.196252	5.196252	5.196252	5.196252	5.196252
	Ωa	24	24	24	24	24	24
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	2.4	0.8	0.24	0.048	0.024	0.016
	$Kr=A^B$	94.55255	0.31364	0.000602	1.4E-07	3.83E-09	4.66E-10
	Ks	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Pred. unsa	**Ku**	1.85E-02	6.15E-05	1.18E-07	2.75E-11	7.51E-13	9.13E-14
		***			****		*****

Table 4.53: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 2.0m depth (Faculty of Environmental Sciences area)



		Depth	2m				
	¥	0.318725	0.318725	0.3187247	0.3187247	0.31872474	0.318724742
	3¥	0.956174	0.956174	0.9561742	0.9561742	0.95617422	0.956174225
	B=3¥+2	2.956174	2.956174	2.9561742	2.9561742	2.95617422	2.956174225
	Ωa	25	25	25	25	25	25
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	2.5	0.833333	0.25	0.05	0.025	0.016666667
	$Kr=A^B$	15.00998	0.583346	0.0166037	0.0001425	1.8367E-05	5.53956E-06
	Ks	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Pred. unsa	Ku	2.94E-03	1.14E-04	3.25E-06	2.79E-08	3.60E-09	1.09E-09
		***			****		*****

Table 4.54: Prediction of unsaturated hydraulic conductivity (Ku) using Brook-Corey model for 2.5m depth (Faculty of Environmental Sciences area)



		Depth	2.5m				
	¥	0.2950686	0.2950686	0.2950686	0.2950686	0.295068611	0.295068611
	3¥	0.8852058	0.8852058	0.8852058	0.8852058	0.885205832	0.885205832
	B=3¥+2	2.8852058	2.8852058	2.8852058	2.8852058	2.885205832	2.885205832
	Ωa	21	21	21	21	21	21
	Ω	10	30	100	500	1000	1500
	A=Ωa/Ω	2.1	0.7	0.21	0.042	0.021	0.014
	$Kr=A^B$	8.5048956	0.3573353	0.011078	0.0001066	1.44297E-05	4.47917E-06
	Ks	2.10E-04	2.10E-04	2.10E-04	2.10E-04	2.10E-04	2.10E-04
Pred. unsa	Ku	1.79E-03	7.50E-05	2.33E-06	2.24E-08	3.03E-09	9.41E-10
		***			****		*****

Table 4.55: Fredlung and Xing model using SWCC parameters (Faculty of Environmental Sciences area)

	Depth	0.5m	1m	1.5m	2m	2.5m
	SATURATE	0.371089	0.389689	0.408016	0.383914	0.377982
	RESIDUAL	0.317804	0.321833	0.357258	0.332851	0.320712
compaction volumetric wate	ORDINAR	0.026642	0.033928	0.025379	0.025531	0.028635
Residual Suction (Ωr)	(Ωr)	1500	1500	1500	1500	1500
Suction @ air entry	Ωa	24	25	24	25	21
Suction @ P	**Ωi = a=A**	230	220	46	220	220
	Y1	0.33	0.33	0.372	0.354	0.333
	Y2	0.334	0.341	0.386	0.364	0.337
	X1	2.146128	2	1.477121	2.079181	2.113943
	X2	2.60206	2.69897	1.875061	2.60206	2.60206
	SLOPE	0.008773	0.015737	0.035181	0.019125	0.008195
	(Ωr) + (Ωi)	1730	1720	1546	1720	1720
Vol water cont. @ P	θ	0.332	0.3345	0.379	0.359	0.335
	Numi	-0.14266	-0.13686	-0.03021	-0.13686	-0.13686
	Denomi	6.503789	6.503789	6.503789	6.503789	6.503789
	C(Ω)	0.978066	0.978957	0.995356	0.978957	0.978957
B	m*	0.327	0.482	0.254	0.168	0.365
	m*+1	1.327	1.482	1.254	1.168	1.365
	B	0.018714	0.017265	0.004272	0.018793	0.017821
	s*	0.005	0.023	0.082	0.031	0.004
C	n*	0.082	0.272	1.694	0.961	0.058

Table 4.56: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 0.5m depth (Faculty of Environmental Sciences area)

Unsat HC	**LEONG & RAHARDJO MODEL (Using Fredlund SWCC parameters)**					
Depth	0.5m					
ψ = suction	10	30	100	500	1000	1500
$\ln(\psi)$	1	1.477121	2	2.69897	3	3.17609126
a = air entry suction	24	24	24	24	24	24
m	0.327101	0.327101	0.327101	0.327101	0.327101	0.32710055
m+1	1.327	1.327	1.327	1.327	1.327	1.327
n	0.082002	0.082002	0.082002	0.082002	0.082002	0.08200223
$(e + (\psi/a)^n)$	3.649006	3.736747	3.842429	4.001027	4.07605	4.12195374
$\ln(e + (\psi/a)^n$	1.294455	1.318215	1.346105	1.386551	1.405128	1.41632726
$(\ln(e + (\psi/a)^n)^m$	1.088087	1.09458	1.102102	1.112826	1.117681	1.12058731
Kr	0.919044	0.913592	0.907357	0.898613	0.894709	0.89238918
Ks	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Ku	1.80E-04	1.79E-04	1.78E-04	1.76E-04	1.75E-04	1.75E-04

Table 4.57: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 1.0m depth (Faculty of Environmental Sciences area)

	Depth	1m					
	ψ = suctio	10	30	100	500	1000	1500
	ln(ψ)	1	1.477121	2	2.69897	3	3.176091
	a = air ent	25	25	25	25	25	25
	m	0.482399	0.482399	0.482399	0.482399	0.482399	0.482399
	m+1	1.482	1.482	1.482	1.482	1.482	1.482
	n	0.271772	0.271772	0.271772	0.271772	0.271772	0.271772
	(e + (ψ/a)^{n}	3.497843	3.769078	4.175828	4.975549	5.443458	5.760927
	ln(e + (ψ/a	1.252146	1.32683	1.429313	1.604536	1.694415	1.751098
	(ln(e + (ψ/	1.114574	1.146162	1.188046	1.256205	1.289671	1.310306
	Kr	0.897204	0.872477	0.841718	0.796049	0.775392	0.76318
	Ks	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04	1.69E-04
	Ku	1.52E-04	1.47E-04	1.42E-04	1.35E-04	1.31E-04	1.29E-04

Table 4.58: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 1.5m depth (Faculty of Environmental Sciences area)

	Depth	1.5m					
	ψ = suctio	10	30	100	500	1000	1500
	ln(ψ)	1	1.477121	2	2.69897	3	3.176091
	a = air ent	24	24	24	24	24	24
	m	0.253653	0.253653	0.253653	0.253653	0.253653	0.253653
	m+1	1.254	1.254	1.254	1.254	1.254	1.254
	n	1.693976	1.693976	1.693976	1.693976	1.693976	1.693976
	(e + (ψ/a)^{n}	2.945231	4.177643	13.93606	174.0923	557.194	1104.706
	ln(e + (ψ/a	1.080187	1.429747	2.63448	5.159586	6.322913	7.007335
	(ln(e + (ψ/	1.019758	1.094919	1.278529	1.516201	1.596448	1.638615
	Kr	0.980625	0.91331	0.782149	0.659543	0.62639	0.610272
	Ks	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
	Ku	1.92E-04	1.79E-04	1.53E-04	1.29E-04	1.23E-04	1.20E-04

Table 4.59: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 2.0m depth (Faculty of Environmental Sciences area)

Depth	2m					
ψ = suctio	10	30	100	500	1000	1500
ln(ψ)	1	1.477121	2	2.69897	3	3.176091
a = air ent	25	25	25	25	25	25
m	0.168187	0.168187	0.168187	0.168187	0.168187	0.168187
m+1	1.168	1.168	1.168	1.168	1.168	1.168
n	0.960848	0.960848	0.960848	0.960848	0.960848	0.960848
(e + (ψ/a)^n	3.13289	3.909745	6.506961	20.50483	37.33898	53.83144
ln(e + (ψ/a	1.141956	1.363472	1.872872	3.020661	3.620038	3.985858
(ln(e + (ψ/	1.022577	1.053527	1.111303	1.204334	1.241562	1.261828
Kr	0.977922	0.949192	0.899845	0.830334	0.805437	0.792501
Ks	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04	1.96E-04
Ku	1.92E-04	1.86E-04	1.76E-04	1.63E-04	1.58E-04	1.55E-04

Table 4.60: Prediction of unsaturated hydraulic conductivity (Ku) using Fredlung and Xing model for 2.5m depth (Faculty of Environmental Sciences area)

Depth	2.5m					
ψ = suctio	10	30	100	500	1000	1500
ln(ψ)	1	1.477121	2	2.69897	3	3.176091
a = air ent	21	21	21	21	21	21
m	0.364976	0.364976	0.364976	0.364976	0.364976	0.364976
m+1	1.365	1.365	1.365	1.365	1.365	1.365
n	0.058093	0.058093	0.058093	0.058093	0.058093	0.058093
(e + (ψ/a)^n	3.676095	3.739216	3.813179	3.920487	3.969883	3.999714
ln(e + (ψ/a	1.301851	1.318876	1.338463	1.366216	1.378737	1.386223
(ln(e + (ψ/	1.101063	1.106297	1.112265	1.120628	1.124365	1.126589
Kr	0.908213	0.903917	0.899066	0.892357	0.889391	0.887635
Ks	2.10E-04	2.10E-04	2.10E-04	2.10E-04	2.10E-04	2.10E-04
Ku	1.91E-04	1.90E-04	1.89E-04	1.87E-04	1.87E-04	1.86E-04

Prediction of volumetric water contents at three locations using the three models (Van genutchen, Brooks-corey, fredlund and Xing).

	TABLE 61: SUMMARY OF PREDICTED VOLUMETRIC WATER CONTENT OF SAMPLE SOILS USING THE THREE MODELS								
	BASEMENT AREA			FACULTY OF EDUCATION			FAC. OF ENVIRONMENT SCIENCE		
kpa	Van genutchen Cm^3Cm^{-3}	Brooks-Corey Cm^3Cm^{-3}	Fredlund and Xing Cm^3Cm^{-3}	Van genutchen Cm^3Cm^{-3}	Brooks-Corey Cm^3Cm^{-3}	Fredlund and Xing Cm^3Cm^{-3}	Van genutchen Cm^3Cm^{-3}	Brooks-Corey Cm^3Cm^{-3}	Fredlund and Xing Cm^3Cm^{-3}
10	0.386493	0.3359	0.325616	0.404992	0.3439	0.33178	0.366262	0.3816	0.367335
30	0.357656	0.3657	0.364428	0.372494	0.3801	0.380236	0.382981	0.3872	0.384129
100	0.375229	0.3835	0.386936	0.358264	0.3536	0.359024	0.38989	0.3951	0.400604
500	0.338923	0.3446	0.352284	0.372476	0.3462	0.355929	0.369146	0.3604	0.380067
1000	0.363549	0.3489	0.370631	0.344458	0.344	0.355556	0.366382	0.3466	0.372213

From the table summary of the predicted volumetric water content of sample soils the three models used predicted above the laboratory values obtained. The comparison of the predicted and laboratory values are close to each other. This validated that the models can be used for volumetric water content prediction of unsaturated soil.

See Appendix B for the predicted details

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATION

Research was carried out in this study and the result presented the general nature of the SWCC for soils with different consistency limits (index properties) and gradation in terms of gravimetric water content versus soil matric suction from locations in university of Benin.

To do this, soil samples were tested to find their SWCC experimentally using pressure plate extractor at the Ahmadu Bello University, Zaria (ABU).

The results were compared with the curves obtained from different models presented in the literature for example Van Genutchen, Fredlund and Xing and Brook- Corey Models.

The result shows a good agreement and also presented a simple method for inferring the SWCC for soils, taking into account the liquid limit, plasticity index and percent of fines passing sieve no-200. The fitting parameters were then obtained to predict the hydraulic conductivity and volumetric water content change for all the soil samples at various depths.

The main conclusions that can be drawn from this study are:

The soil-water characteristic curve has been identified as key soil information required for the analysis of seepage and volumetric change problems involving unsaturated soils.

The soil-water characteristics curves (SWCC) of fifteen specimens obtained from three tropical soils samples were developed based on data from laboratory pressure plate extractor test.

The pressure plate extractor employs the axis translation technique to yield water contents the SWCC data were used to determine the fitting parameters to three most commonly used soil-water retention models. The models also formed the basis for the prediction of hydraulic conductivity and volumetric water content (θ) for the soil specimens.

The predicted unsaturated hydraulic conductivity of specimens was determined using the Van Genuchten (VG), Brooks-Corey (BC), as well as Fredlund-Xing (FX) models.

The result shows that: Generally, Van Genuchten and Brooks-Corey models over predicted volumetric water content (θ) at low suctions, while Fred Lund-Xing model under predicted it but the values are close to laboratory measured values.

This study has really validated that engineering properties of unsaturated soils such as the hydraulic conductivity and volumetric water content properties can be predicted reasonably well using the soil-water characteristics curve.

Lateritic soil occur extensively in Nigeria and have potential uses as barrier material for engineering landfill anti piping materials in the construction of earthdams.
Soil suctions is inversely proportional to volumetric change.

5.1 RECOMMENDATION

The following recommendations are made on the basis of the finding of this study.
Lateritic soil - can be used as barrier materials if this blended with other soil with similar geotechnical characteristics because it provides excellent geotechnical/ geo environmental performance.

There are limited experimental studies available in literature with respect to the engineering behavior of unsaturated soils in the high suction range. Experimental studies on different soils are to be undertaken to better understand the conceptual role of residual state conditions on the engineering behavior of unsaturated soils.

It is anticipated that there will be an increase in the research related to use the soil-water characteristics curve data for the estimation of unsaturated soil property functions. Therefore more researches are to be employed for deep knowledge of SWCC.

Relationships of soil-water potentials and hydraulic conductivity with soil-water content are necessary for many soil-water related investigations such as water conservations, irrigation scheduling, and drainage etc.

Fredlund-Xing models which gave values closer to the laboratory measured values can be used to predict soil water characteristics curve (SWCC) at low suction.

The primary functions of liners in a land fill is to prevent the release of contaminants from the unit into the adjoining soil and therefore the hydraulic conductivity should be as low as less them 1 x10^{-9}- m/s to be effective in the containment of municipal solid waste and in the construction of earth dams especially the upstream side.

Hydraulic conductivity is the basic parameter for design and characterization of landfill performance and reliability. The experiment should be extended to other soil types for their hydraulic conductivity.

One of the most important applications for this thesis work is in pavement design; where the unsaturated soil mechanics plays an important role in the performance of the pavement structure, mainly on the resistance and deformation of the soil. These characteristics of the soil are mainly due to variations in matric suction, which could take place due to changes on external conditions especially due to presence of water, changes in temperature, depth of the ground water table, external loads, etc. This relationship between the matric suction and the amount of water into the soil has been considered in the Enhanced Integrated Climatic Model (EICM) as part of the Mechanistic– Empirical Pavement Design Guide (MEPDG).

Therefore geotechnics and geo-environmental engineers should endeavor to comply with AASHTO 2008 approved Mechanistic Empirical Pavement Design Guide (MEPDG) by using the SWCC tool

5.2 CONTRIBUTION TO KNOWLEDGE

Fredlund and Xing models is the best used for the prediction of unsaturated hydraulic conductivity in the Vadose zone. The knowledge of the hydraulic conductivity (K) cannot be overemphasized because it regulates the water flows in this zone.

For design engineers SWCC curves are the best tools to be used for design land fill liners and prevention of piping in earthdams construction.

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Maigien, 1966; Newill and Dowling, 1970; Gdigasu, 1975; Fookes, 1997

Maigien, 1966; Townsend et al.,1971; Charman, 1988; Rowe et al., 1995.

Maignien, 1966.

Maignien, 1966; Gidigasu, 1976

Maignien, 1966; Gidigasu, 1976; Charman, 1988; Fookes, 1997

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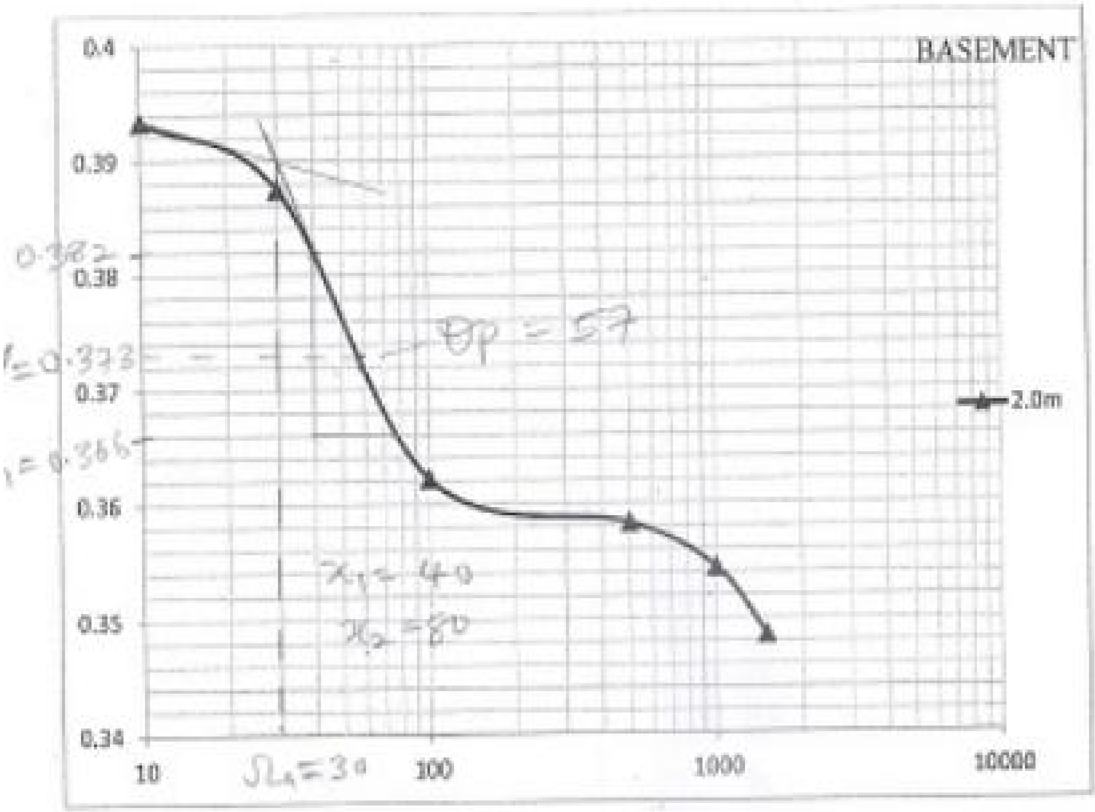
APPENDICES

APPENDIX

A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0.38
=0.373
0.37
=0.366
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0.34
Dp = 57
x1 = 40
x2 = 80
10
Ω1 = 30
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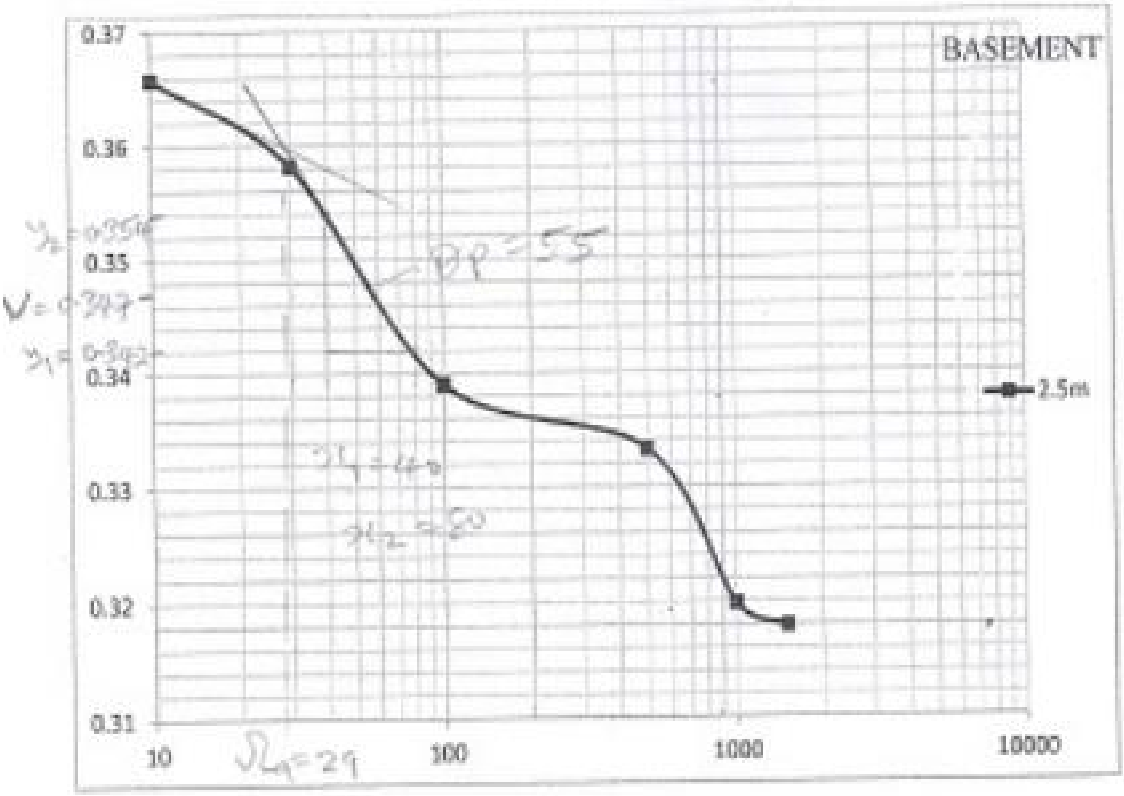
1000
10000
2.0m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x2 = 80
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Ω1 = 29
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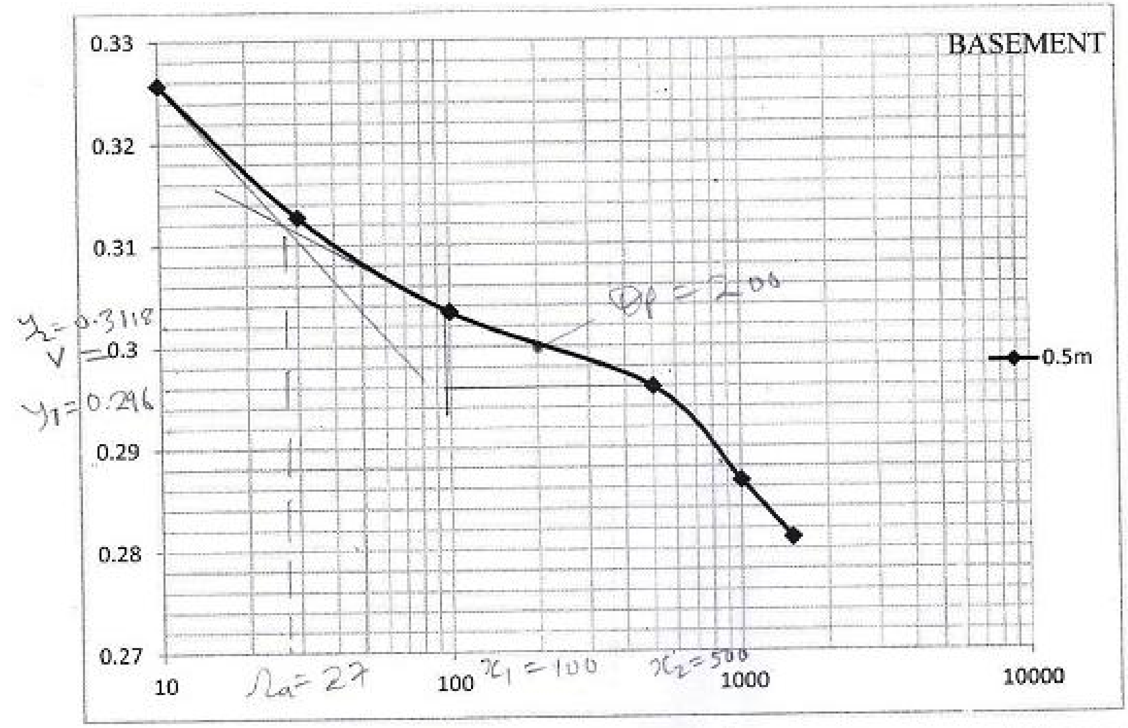
1000
10000
2.5m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y1 = 0.296
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Ωa = 27
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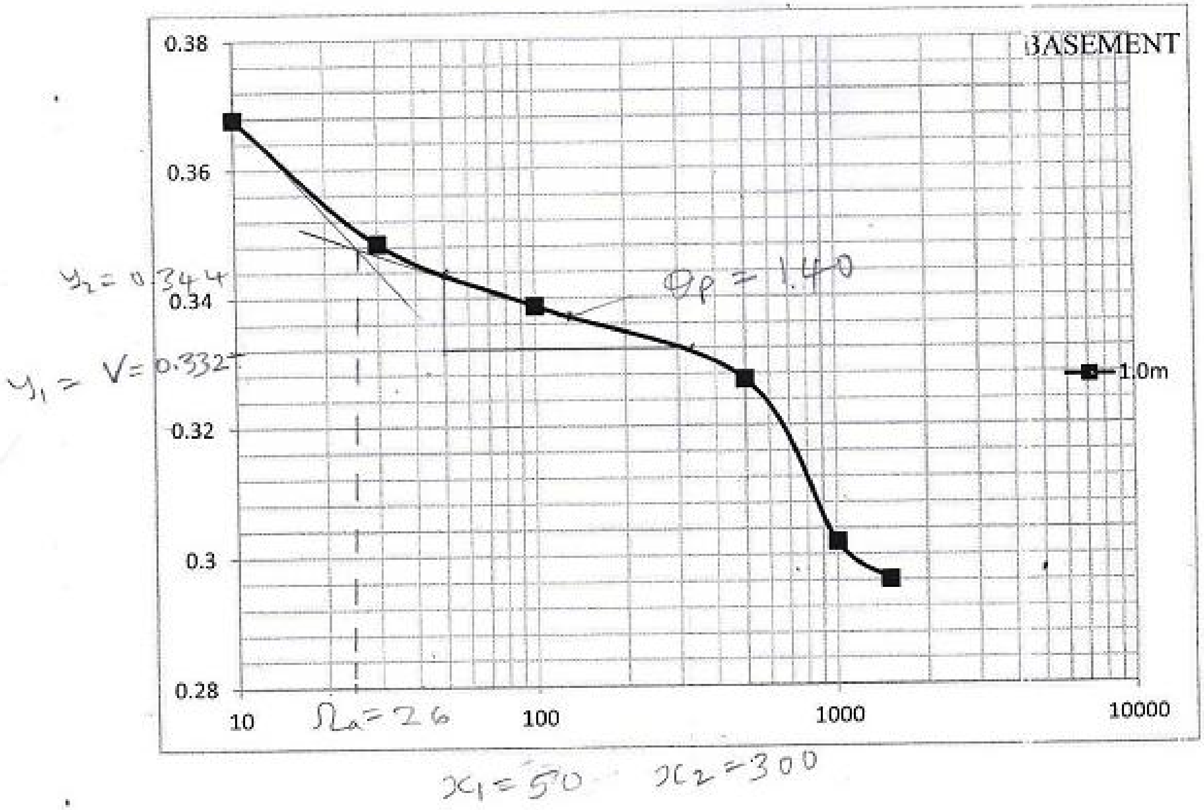
x2 = 500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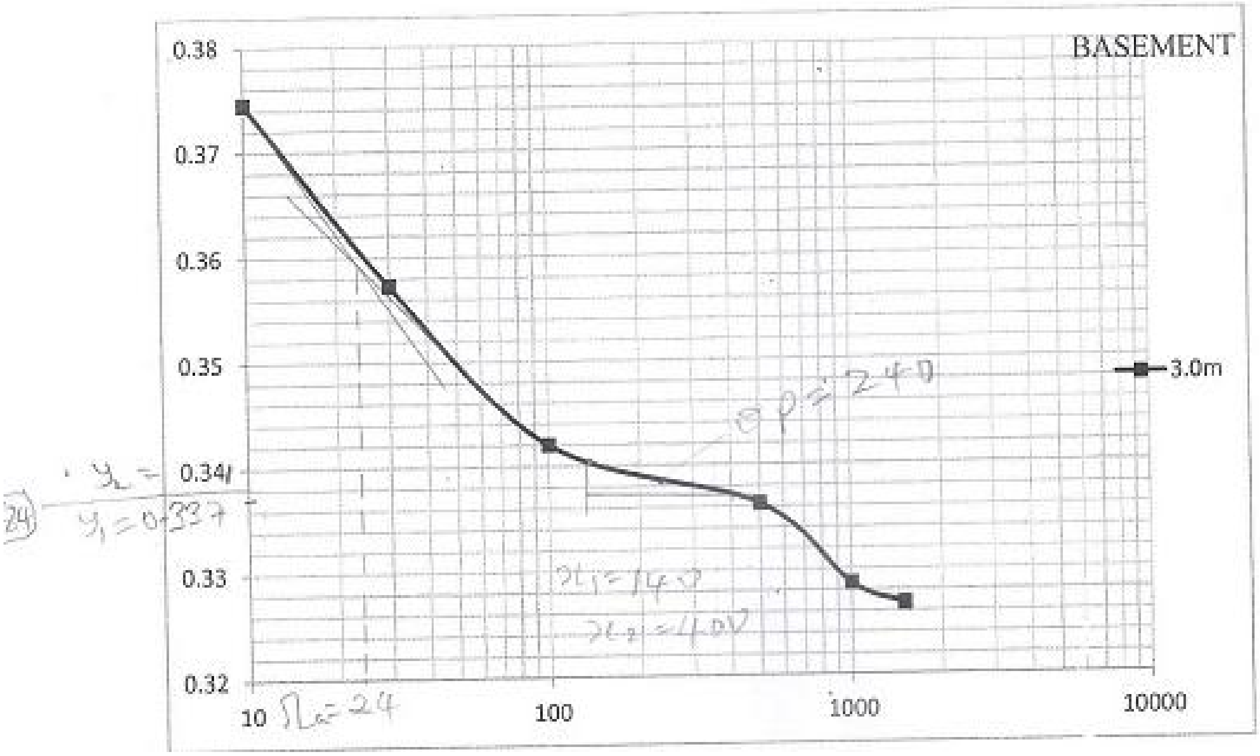
x2 = 300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0.34
0.33
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1000
10000
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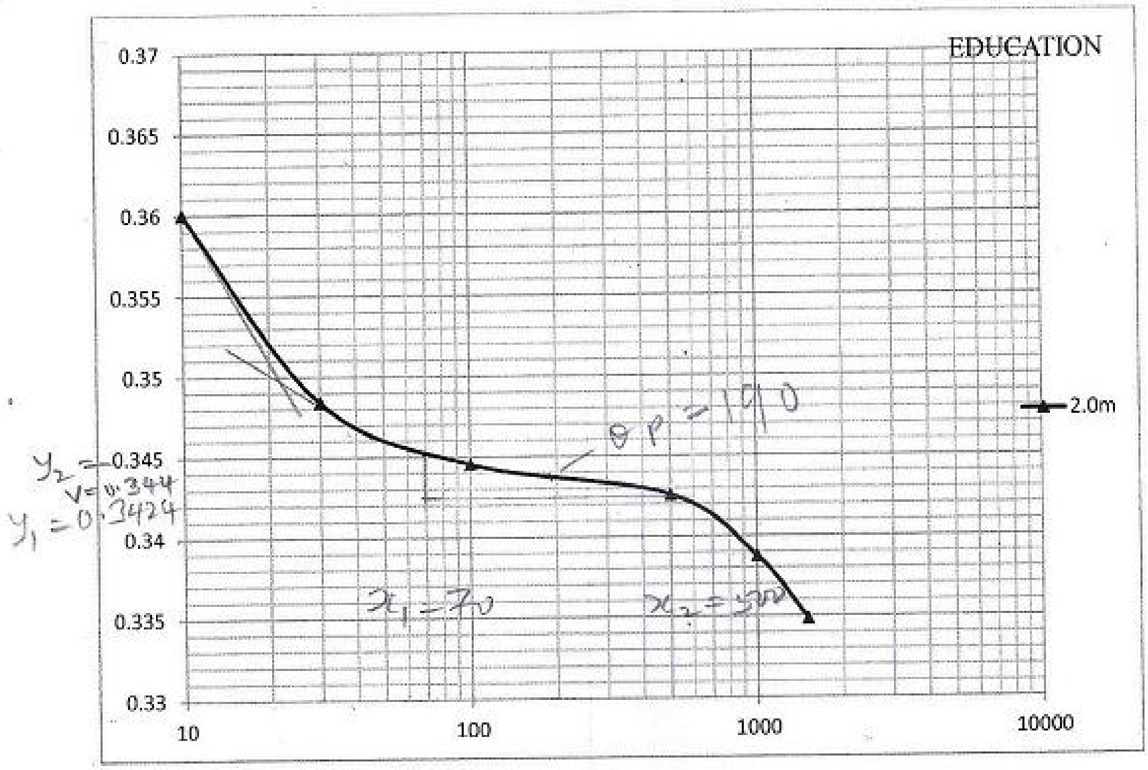
y2 = 0.341
y1 = 0.337
σp = 240
x1 = 140
x2 = 400
σc = 24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0.35
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0.34
0.335
0.33
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100
1000
10000
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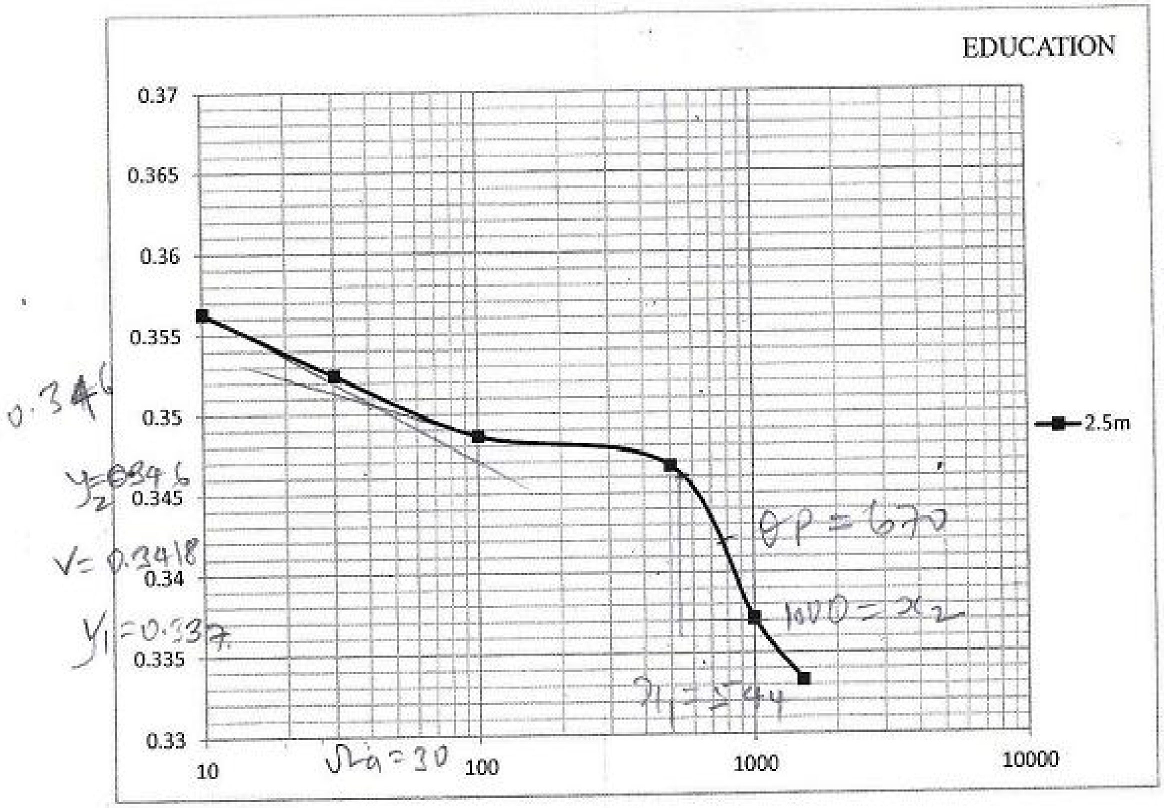
x_2 = 500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1000
10000
2.5m
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v = 0.3418
y_1 = 0.337
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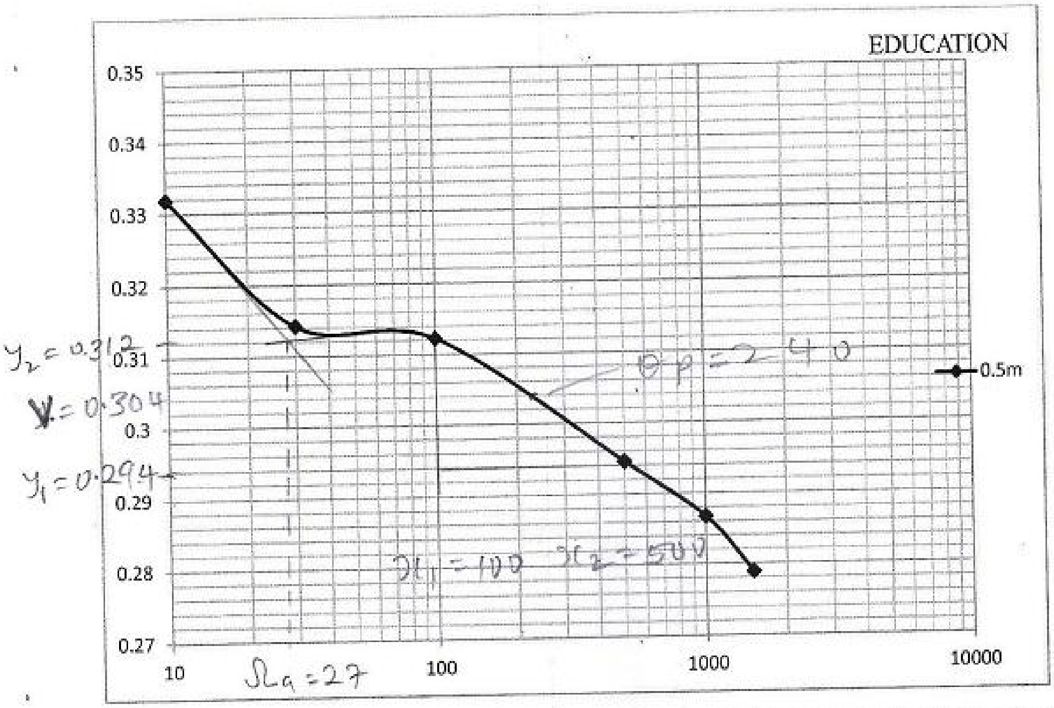
1000 = x_2
x_1 = 544
Ωa = 30



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0.27
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100
1000
10000
0.5m
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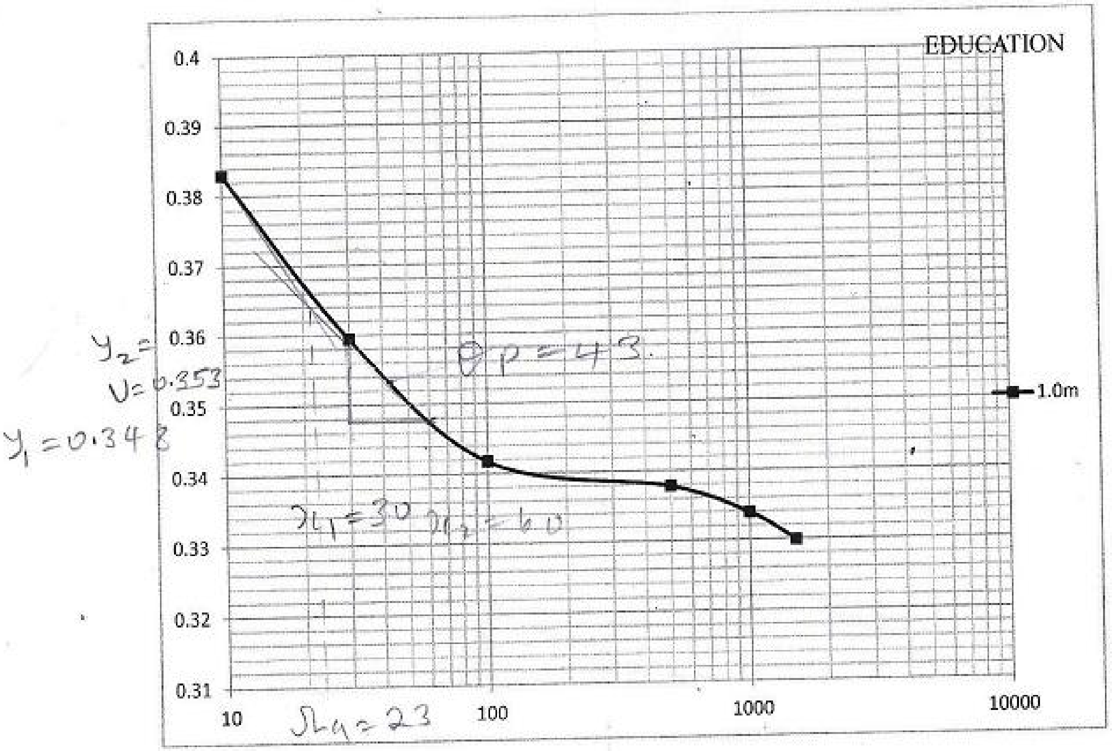
Ωa = 27



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0.34
0.33
0.32
0.31
10
100
1000
10000
1.0m
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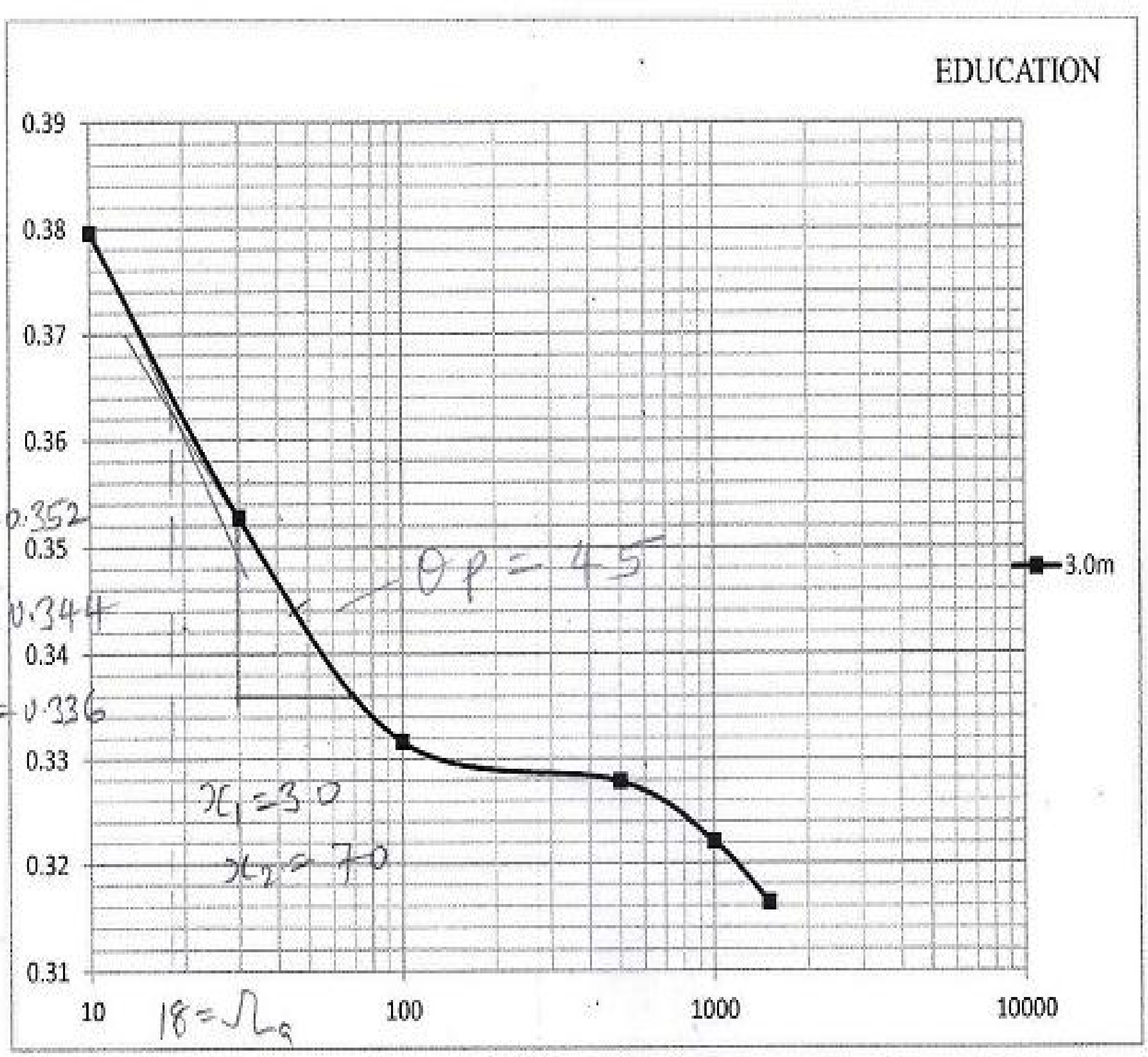
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0.33
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0.31
10
100
1000
10000
3.0m
$y_2 = 0.352$
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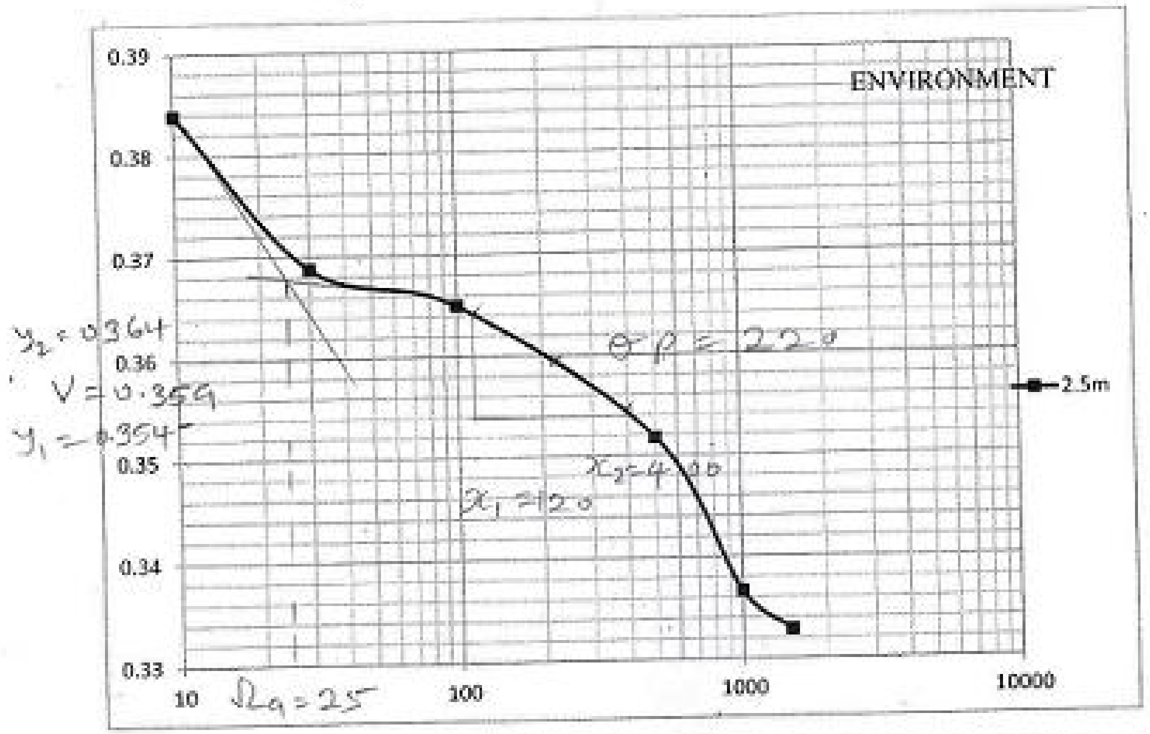
$y_1 = 0.336$
$\theta p = 45$
$x_1 = 30$
$x_2 = 70$
$18 = \Omega_a$


ENVIRONMENT
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0.34
0.33
10
100
1000
10000
2.5m
$y_2 = 0.364$
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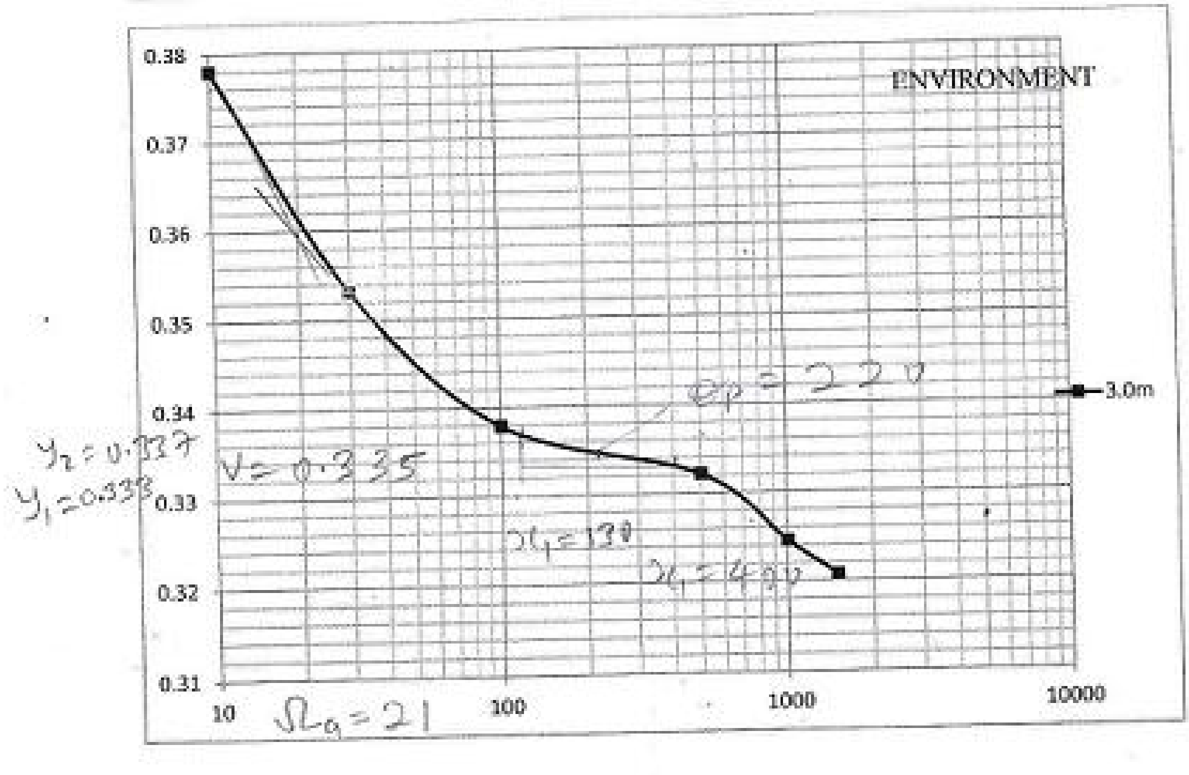
$x_2 = 400$
$x_1 = 120$
$\Omega_a = 25$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0.37
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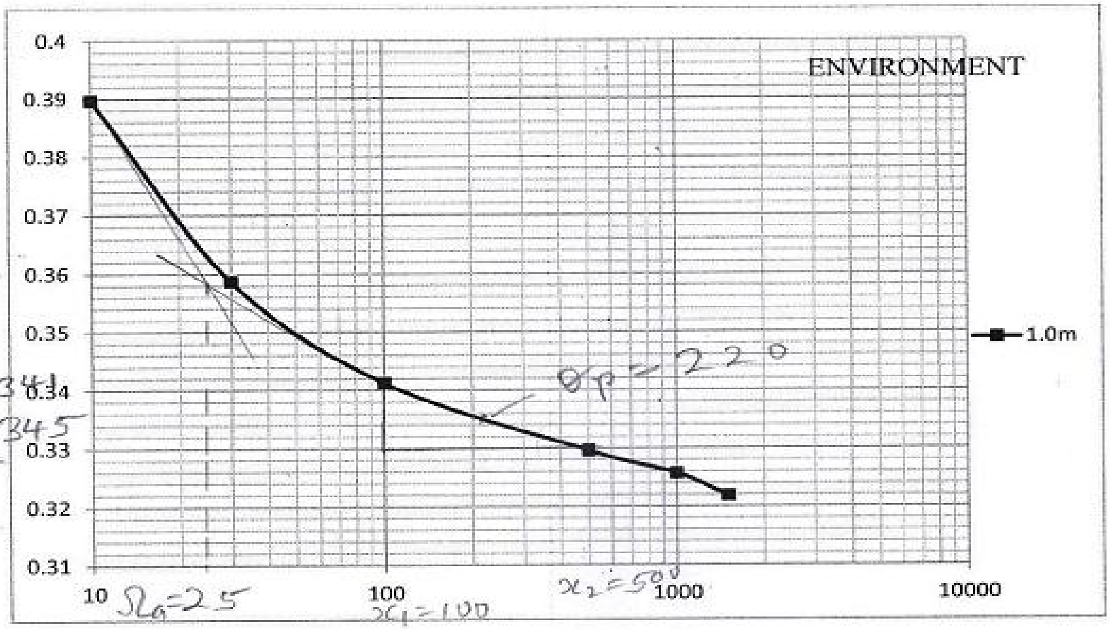
0.35
0.34
0.33
0.32
0.31
10
100
1000
10000
3.0m
$\theta p = 220$
$y_2 = 0.337$
$y_1 = 0.338$
$V = 0.335$
$x_4 = 130$
$x_1 = 490$
$\Omega_a = 21$

$y_2 = 0.341$

$y_2 = 0.341$

$V = 0.3345$

$y_1 =$



$\theta_p = 220$

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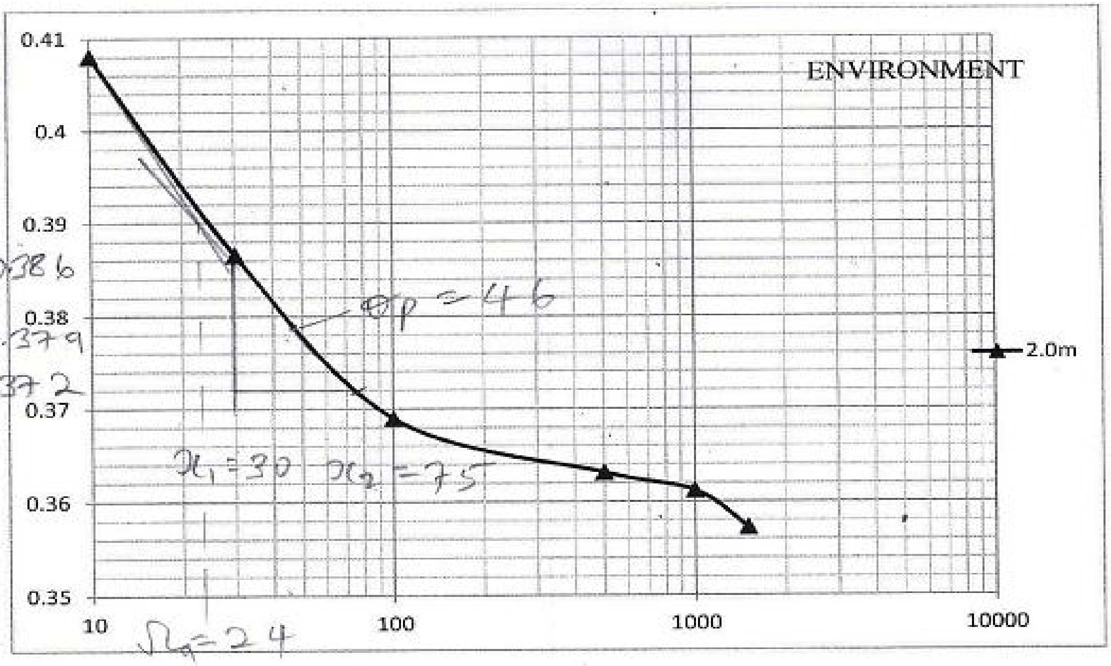
$x_1 = 100$

$x_2 = 500$

$y_2 = 0.386$

$V = 0.379$

$y_1 = 0.372$



$\theta_p = 46$

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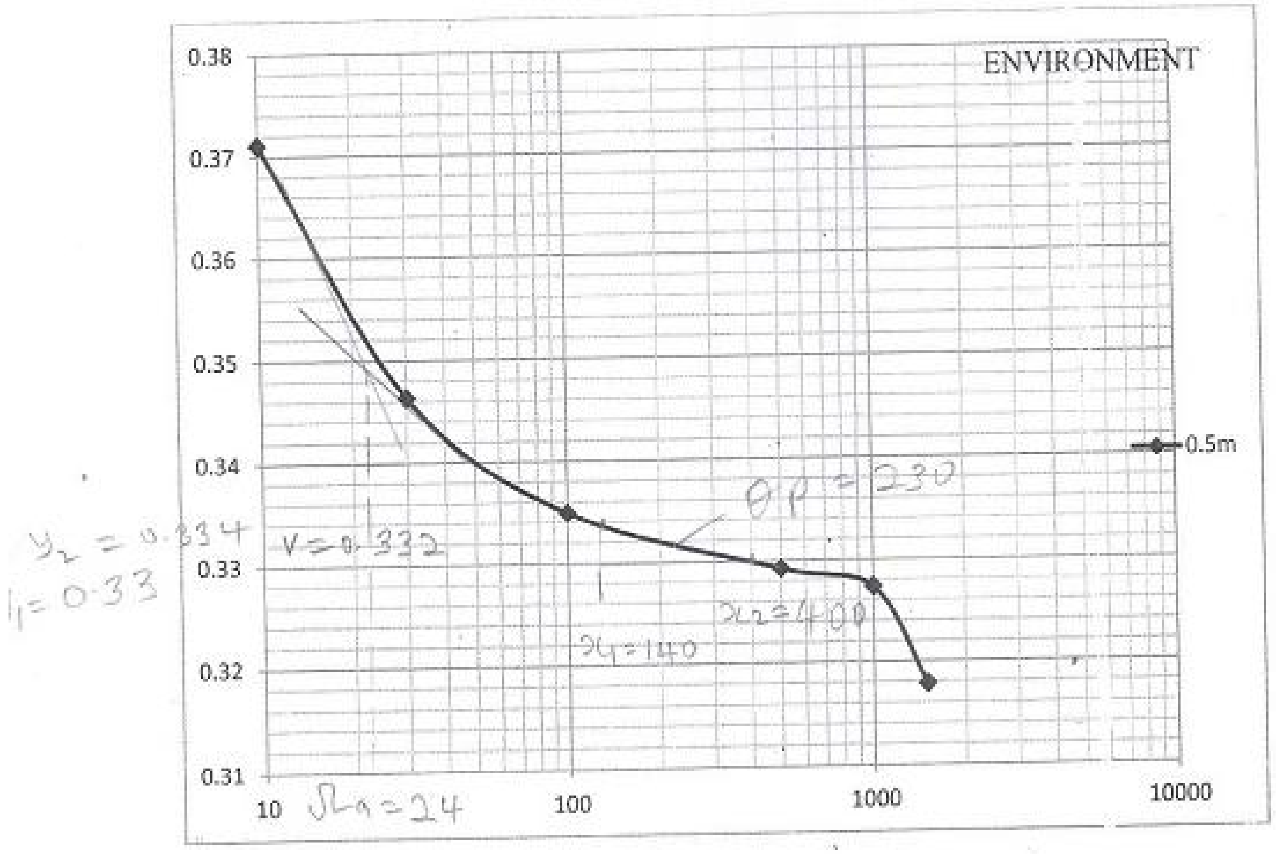
$\Omega_a = 24$


ENVIRONMENT
0.38
0.37
0.36
0.35
0.34
0.33
0.32
0.31
10
100
1000
10000
0.5m
y2 = 0.334
y1 = 0.33
V = 0.332
θp = 230
x1 = 140
x2 = 400
Ωa = 24

APPENDIX B

MODEL of Volumetric water content Fredlung and Xing (Education)

Leong and Rahardjo matric sunction model using (Optimum moisture content)BS					
SATURATED	0.331879	0.382937	0.360014	0.356287	0.379598
RESIDUAL	0.278857	0.329915	0.334852	0.3333	0.316331
φs-φr=g	0.053	0.053	0.025	0.023	0.063
Ωa	27	23	24	30	18
SUCTION USED IN THE LAB, Ω	10	30	100	500	1000
Suction @ P, Ωi = a	240	43	190	670	45
m	0.303	0.227	0.148	0.132	0.273
n	1.279	0.612	0.015	3.430	1.851
C(Ω)	0.99348	0.99348	0.99348	0.99348	0.99348
e	2.718	2.718	2.718	2.718	2.718
Ω/a	0.041667	0.697674	0.526316	0.746269	22.22222
$(\Omega/a)^n$	0.017153	0.802133	0.990351	0.366419	310.8716
$e + (\Omega/a)^n$	2.735153	3.520133	3.708351	3.084419	313.5896
$\ln(e + (\Omega/a)^{n)}$	1.006187	1.258499	1.310587	1.126363	5.748085
$[\ln(e + (\Omega/a)^{n]m}$	1.001874	1.053682	1.040967	1.015827	1.61294
Preditecφ (Leong and Rahardjo)	0.33178	0.380236	0.359024	0.355929	0.355556

MODEL of Volumetric water content Brooks-Corey (Faculty of Education)

SATURATED	0.331879	0.382937	0.360014	0.356287	0.379598
RESIDUAL	0.278857	0.329915	0.334852	0.3333	0.316331
Ωa	27	23	24	30	18
φs-φr=g	0.053	0.053	0.025	0.023	0.063
Ω	10	30	100	500	1000
(Ωa/Ω)	2.7	0.766667	0.24	0.06	0.018
$(\Omega a/\Omega)^{¥}$	1.227046	0.946736	0.745287	0.560143	0.437105
$g(\Omega a/\Omega)^{¥}$	0.065061	0.050198	0.018753	0.012876	0.027654
φcorey	0.3439	0.3801	0.3536	0.3462	0.3440

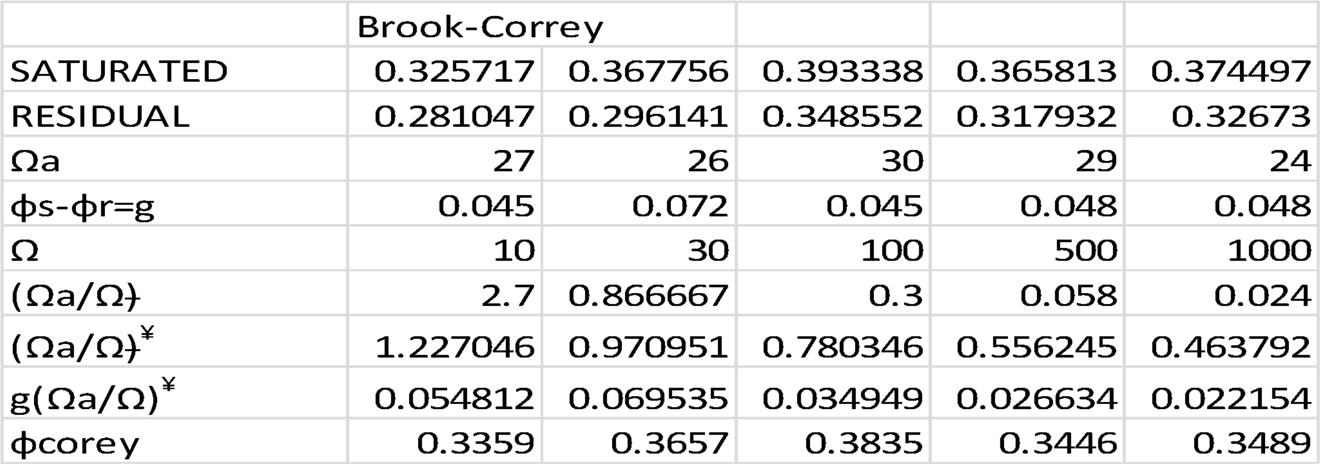
MODEL of Volumetric water content Van genutchen (Faculty of Education)

	prediction of volumetric water content vangenutchen					
	omc 0	0% RBSL				
	SATURATED	0.331879	0.382937	0.360014	0.356287	0.379598
	RESIDUAL	0.278857	0.329915	0.334852	0.3333	0.316331
	Ωa	27	23	24	30	18
	ϕs-ϕr=g	0.053	0.053	0.025	0.023	0.063
SUCTION USED IN THE LAB	Ω	10	30	100	500	1000
	m	0.32	0.22	0.06	0.71	0.42
	n	1.47	1.28	1.06	3.45	1.73
	ALPHA	0.016	0.256	0.257	0.002	0.051
	Ω*ALPHA=A	0.164965	7.681781	25.7	0.863595	50.51197
	A^n	0.070109	13.72923	31.36773	0.603086	895.0962
	1+An	1.07E+00	1.47E+01	3.24E+01	1.60E+00	8.96E+02
	(ln(1+A^n))	0.067761	2.689834	3.477162	0.471931	6.798048
	B=(ln(1+$A^{n)}$)^m	0.42036	1.245254	1.074737	0.586751	2.249323
	1/B	2.378916	0.803049	0.930461	1.704302	0.444578
	1/B*g	0.126135	0.042579	0.023413	0.039175	0.028127
PREDICTED SWCC	ϕvan=(1/B*g)+ϕr	0.404992	0.372494	0.358264	0.372476	0.344458

MODEL of Volumetric water content Fredlund and Xing (Basement)

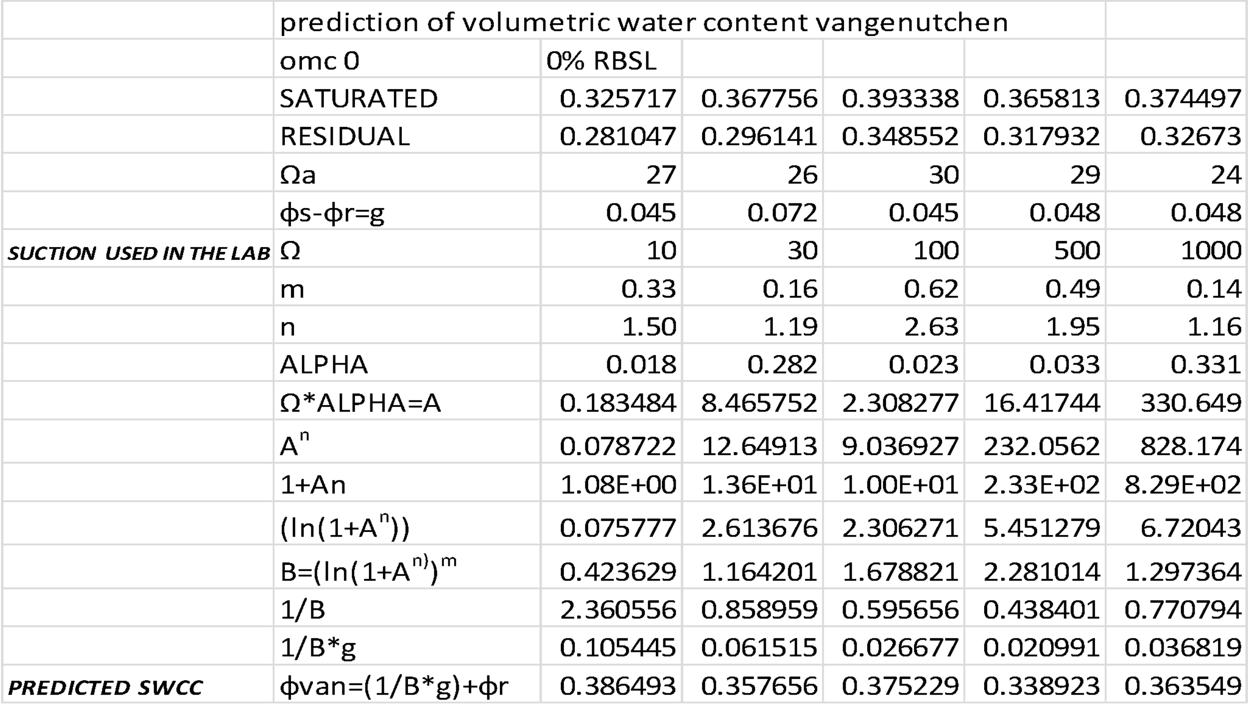
Leong and Rahardjo matric sunction model using (Optimum moisture content)BS					
SATURATED	0.325717	0.367756	0.393338	0.365813	0.374497
RESIDUAL	0.281047	0.296141	0.348552	0.317932	0.32673
ϕs-ϕr=g	0.045	0.072	0.045	0.048	0.048
Ωa	27	26	30	29	24
SUCTION USED IN THE LAB, Ω	10	30	100	500	1000
Suction @ P, Ωi = a	200	140	57	55	240
m	0.231	0.325	0.174	0.173	0.287
n	1.202	0.497	3.836	3.074	0.071
C(Ω)	0.99348	0.99348	0.99348	0.99348	0.99348
e	2.718	2.718	2.718	2.718	2.718
Ω/a	0.05	0.214286	1.754386	9.090909	4.166667
$(\Omega/a)^n$	0.027297	0.465158	8.640476	884.0487	1.107151
$e + (\Omega/a)^n$	2.745297	3.183158	11.35848	886.7667	3.825151
ln(e + $(\Omega/a)^{n)}$	1.009889	1.157874	2.429964	6.787582	1.341598
[ln(e + $(\Omega/a)^{n]m}$	1.002271	1.048745	1.166795	1.393828	1.088078
Preditecϕ (Leong and Rahardjo)	0.325616	0.364428	0.386936	0.352284	0.370631

MODEL of Volumetric water content Brooks-Corey (Basement)



	Brook-Correy				
SATURATED	0.325717	0.367756	0.393338	0.365813	0.374497
RESIDUAL	0.281047	0.296141	0.348552	0.317932	0.32673
Ωa	27	26	30	29	24
ϕs-ϕr=g	0.045	0.072	0.045	0.048	0.048
Ω	10	30	100	500	1000
(Ωa/Ω)	2.7	0.866667	0.3	0.058	0.024
(Ωa/Ω)$^{¥}$	1.227046	0.970951	0.780346	0.556245	0.463792
g(Ωa/Ω)$^{¥}$	0.054812	0.069535	0.034949	0.026634	0.022154
ϕcorey	0.3359	0.3657	0.3835	0.3446	0.3489

MODEL of Volumetric water content Van genutchen(Basement)



	prediction of volumetric water content vangenutchen					
	omc 0	0% RBSL				
	SATURATED	0.325717	0.367756	0.393338	0.365813	0.374497
	RESIDUAL	0.281047	0.296141	0.348552	0.317932	0.32673
	Ωa	27	26	30	29	24
	ϕs-ϕr=g	0.045	0.072	0.045	0.048	0.048
SUCTION USED IN THE LAB	Ω	10	30	100	500	1000
	m	0.33	0.16	0.62	0.49	0.14
	n	1.50	1.19	2.63	1.95	1.16
	ALPHA	0.018	0.282	0.023	0.033	0.331
	Ω*ALPHA=A	0.183484	8.465752	2.308277	16.41744	330.649
	A^{n}	0.078722	12.64913	9.036927	232.0562	828.174
	1+An	1.08E+00	1.36E+01	1.00E+01	2.33E+02	8.29E+02
	(ln(1+A^{n}))	0.075777	2.613676	2.306271	5.451279	6.72043
	B=(ln(1+A$^{n)}$)^{m}	0.423629	1.164201	1.678821	2.281014	1.297364
	1/B	2.360556	0.858959	0.595656	0.438401	0.770794
	1/B*g	0.105445	0.061515	0.026677	0.020991	0.036819
PREDICTED SWCC	ϕvan=(1/B*g)+ϕr	0.386493	0.357656	0.375229	0.338923	0.363549

MODEL of Volumetric water content Leon and Rahardjo (Faculty of Environmental)

Leong and Rahardjo matric sunction model using (Optimum moisture content)BSI					
SATURATED	0.371089	0.389689	0.408016	0.383914	0.377982
RESIDUAL	0.317804	0.321833	0.357258	0.332851	0.320712
ϕs-ϕr=g	0.053	0.068	0.051	0.051	0.057
Ωa	24	25	24	25	21
SUCTION USED IN THE LAB, Ω	10	30	100	500	1000
Suction @ P, Ωi = a	230	220	46	220	220
m	0.327	0.482	0.254	0.168	0.365
n	0.082	0.272	1.694	0.961	0.058
C(Ω)	0.99348	0.99348	0.99348	0.99348	0.99348
e	2.718	2.718	2.718	2.718	2.718
Ω/a	0.043478	0.136364	2.173913	2.272727	4.545455
$(\Omega/a)^{n}$	0.773277	0.581883	3.726319	2.200836	1.091944
$e + (\Omega/a)^{n}$	3.491277	3.299883	6.444319	4.918836	3.809944
$\ln(e + (\Omega/a)^{n)}$	1.250268	1.193887	1.863199	1.593072	1.337615
$[\ln(e + (\Omega/a)^{n]m}$	1.075796	1.089249	1.170987	1.081467	1.112008
Preditecϕ (Leong and Rahardjo)	0.367335	0.384129	0.400604	0.380067	0.372213

MODEL of Volumetric water content Brooks-Corey (Faculty of Environmental Sciences)

	Brook-Corey				
SATURATED	0.371089	0.389689	0.408016	0.383914	0.377982
RESIDUAL	0.317804	0.321833	0.357258	0.332851	0.320712
Ωa	24	25	24	25	21
ϕs-ϕr=g	0.053	0.068	0.051	0.051	0.057
Ω	10	30	100	500	1000
(Ωa/Ω)	2.4	0.833333	0.24	0.05	0.021
$(\Omega a/\Omega)^{¥}$	1.197632	0.963138	0.745287	0.539495	0.451208
$g(\Omega a/\Omega)^{¥}$	0.063815	0.065355	0.037829	0.027548	0.025841
ϕcorey	0.3816	0.3872	0.3951	0.3604	0.3466

MODEL of Volumetric water content Van genutchen (Faculty of Environmental)

	prediction of volumetric water content vangenutchen					
	omc 0	0% RBSL				
	SATURATED	0.371089	0.389689	0.408016	0.383914	0.377982
	RESIDUAL	0.317804	0.321833	0.357258	0.332851	0.320712
	Ωa	24	25	24	25	21
	ϕs-ϕr=g	0.053	0.068	0.051	0.051	0.057
SUCTION USED IN THE LAB	Ω	10	30	100	500	1000
	m	0.12	0.17	0.43	0.26	0.11
	n	1.14	1.20	1.74	1.35	1.12
	ALPHA	0.596	0.134	0.049	0.031	1.377
	Ω*ALPHA=A	5.957553	4.029308	4.886203	15.67752	1377.276
	A^{n}	7.659281	5.35324	15.83213	41.00734	3309.218
	1+An	8.66E+00	6.35E+00	1.68E+01	4.20E+01	3.31E+03
	$(\ln(1+A^{n}))$	2.158632	1.848965	2.82329	3.737844	8.104769
	$B=(\ln(1+A^{n)})^{m}$	1.099618	1.109692	1.555457	1.406879	1.253985
	1/B	0.909407	0.901151	0.642898	0.710793	0.797458
	1/B*g	0.048457	0.061149	0.032632	0.036295	0.04567
PREDICTED SWCC	ϕvan=(1/B*g)+ϕr	0.366262	0.382981	0.38989	0.369146	0.366382

This topic is very apt because very many of our structures are built in/on unsaturated soils. But you know that the geotechnical practitioners insist in designing the structures these based on saturated soil mechanics. The design of structures based on unsaturated soil mechanics is desirable because it reduces cost and it is by far a more sustainable approach. Infact, researchers have identified the SWCC as the most important soil property when dealing with unsaturated conditions, though it is unpopular among practitioners because the laboratory testing takes an appreciable amount of time and also the specialized equipment and training needed.

SWCC is a graphical representation of the mathematical relationship between the matric suction of a soil (defined as the difference between the pore air pressure **(U_a)** and the pore water pressure **(U_w)**) and either its water content (gravimetric or volumetric) or degree of saturation (**S_r**).

As it was mentioned above, it is vital when solving engineering problem or designing in unsaturated soil. For example, this function allows for the determination of the hydraulic conductivity at different degrees of water content or saturation, which is very important when estimating fluid flow underneath covered areas such as foundations and pavement systems.

Since the experimental procedures, in which a filter paper or pressure plate test, adopted for determining the matric suction- water content relationship is time- consuming and cost- intensive, recent research has placed a major focus on an estimation method to produce the SWCC using some mathematical functions (indirect determination)

In 2008, AASHTO approved the Mechanistic Empirical Pavement Design Guide (MEPDG). This new pavement design guide incorporates the effects of environmental conditions such as precipitation and temperature in the determination of changes of unbound material properties during the life of the pavement structure. This model makes use of unsaturated soil principles which in turn requires the input of the SWCC. To aid in the implementation of the MEPDG in Nigeria a deep knowledge of unsaturated tropical soil mechnics is required and this can be determined through SWCC via laboratory testing.