ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF CIVIL ENGINEERING

# PREDICTION OF SOIL WATER CHARACTERISTIC CURVE BASED ON GSD AND PI FOR RED CLAY AND EXPANSIVE SOILS FOUND IN ADDIS ABABA

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**School of Graduate Studies of Addis Ababa Institute of Technology**

**In Partial Fulfillment of the Requirement for the Degree of**

**Master of Science in Civil Engineering**

By

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Advisor

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**August, 2013**

**Addis Ababa, Ethiopia**

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# LIST OF SYMBOLS

| | |
|---|---|
| SWCC | Soil-water characteristic curve |
| ua | Pore air Pressure |
| uw | Pore water Pressure |
| h or (ua-uw) | Matric suction |
| c’ | Effective cohesion |
| □’ | Effective internal angle of friction |
| □$^{b}$ | Angle indicating the rate of increase in shear strength relative to matric suction |
| τ | Shear stress |
| σ | Normal stress |
| LL | Liquid limit |
| PI | Plasticity index |
| PL | Plastic limit |
| $P_{200}$ | Soil finer than sieve no 200(0.075µm) |
| BS | British Standard Methods of test |
| ASTM | American Society for Testing and Materials |
| AASHTO | American Association of State Highway and Transportation Officials |
| USCS | Unified Soil Classification System |
| GSD | Grain Size Distribution |

# ABSTRACT

Many researchers have done researches on unsaturated soil mechanics worldwide to bring the unsaturated soil mechanics in to practices. Among those researches some of them focused on simplifying the complex and expensive testing mechanism by developing models which can be used to predict the unsaturated soil parameters from basic soil prosperities such as Grain Size Distribution (GSD) and Plasticity Index (PI) along with the saturated shear strength parameters. Soil water characteristic curve (SWCC) was proved to have good relationship with the unsaturated soil parameters. In this study an attempt was made to check whether those developed models would work for expansive and red clay soils found in Addis Ababa.

Using the model developed by Fredlund and Xing (1994) along with the correlation equation given by Perera et.al (2005), family of SWCC for soils found in Addis Ababa has been plotted. It was observed that the family of SWCC plotted was out of the widely referenced family of curves developed by Zapata et.al (2000) to some extent. Even though the family of curves seems to be out of the range provided by Zapata et.al (2000), the model gave good prediction for the unsaturated shear strength parameter Φb.

The percentage error between the measured values of unsaturated shear strength parameter $\Phi_b$ in previous researches of Habtom (2010) and Getaneh (2010) with predicted unsaturated shear strength parameter $\Phi_b$ in this study was compared.

For red clay samples the percentage error lie in the range 2.07 to 6.37% for suction ranges of 36.67 to 52.9 kPa and at lower suctions of 16.75 and 21.5 kPa the percentage error ranges from 11.42 to 25.39% .

For expansive soil samples for suction of 23.1 and 32.9 kPa, the percentage error is in the range from 3.86 to 6.13%. For suction values of 14.5 and 52 kPa the range of error is about 9.45 to 13.40% and for suctions of 38.8 and 48.6 kPa the error lies between 18.94 and 38.84%.

# CHAPTER 1

## 1. INTRODUCTION

### 1.1. Background of the problem

Soil mechanics is divided in to two main divisions namely saturated and unsaturated soil mechanics. Saturated soil mechanics is advanced ahead of unsaturated soil mechanics due to simplicity of its application in most of the engineering practice. The complexity of the nature of unsaturated soil mechanics made engineers to focus on the saturated soil mechanics even though it did not describe the nature of unsaturated soils encountered in practice.

Nowadays, to bring the unsaturated soil mechanics in to practice, several researches are being conducted worldwide. These researches were aimed at simplifying the application of the unsaturated soil mechanics by providing empirical relationship between the simple tests and those that require complex testing apparatus and procedures. The empirical relationship developed to predict soil water characteristics curve (SWCC) based on grain size distribution (GSD) and index properties for plastic and non-plastic soils was among the outcome of those researches.

The equipment required to measure the unsaturated soil property functions becomes costly and demanding; thus making its usage unacceptable for most routine engineering applications. Consequently, the need arises for practical solutions for the determination of unsaturated soil property function. Soil–water characteristic curves have emerged as a practical and sufficient estimation tool for obtaining unsaturated soil property functions.

The soil-water characteristic curve (SWCC) represents the relationship between matric suction and water content for a particular soil. The determination of SWCC of a soil by experimental procedures requires specialized unsaturated soil testing equipment, testing experience, and lengthy testing programs.

From the outcome of many researches that were conducted on unsaturated soil mechanics it was observed that soil-water characteristic curve of the soil can be predicted with a reasonable degree of accuracy using laboratory test results of grain size distribution and Atterberg limits.

This problem can be simplified by creating a relationship between SWCC, GSD and index properties. Using the predicted SWCC and the saturated shear strength parameters it is possible to determine the unsaturated shear strength parameters.

### 1.2. Objectives of the study

The main objectives of this study are:

i) To develop SWCC curves for red clay and expansive soils found in Addis Ababa based on existing numerical models developed in other countries; and
ii) To investigate whether these models are applicable in the prediction of unsaturated shear strength parameters for Addis Ababa red clay and expansive soils.

### 1.3. Methodology

In this research previous studies related to unsaturated soil mechanics in general and developments of SWCC curves in particular have been reviewed. As part of methodology to perform the research, sample collection from selected locations within the study area and different laboratory tests have been carried out on those samples according to ASTM standards. Based on the theories discussed in the literature review; laboratory test results from previous researches done on expansive and red clay soils found in Addis Ababa by Habtom,2010 and Getaneh,2010 respectively; and laboratory tests performed in this study, the results obtained have been analyzed and discussed thoroughly. Finally, the findings and results of the research have been reported.

### 1.4. Scope of the study

This research focuses on different locations within Addis Ababa where red clay and expansive soils are prevalent. Red clays were known to be found in Northern and Western parts of Addis Ababa (Samuel, 1989) while expansive soils were prevalent in eastern and southern part of Addis Ababa (Ayenew, 2004). Specifically for this research samples were collected from eight test pits dug to a depth of 2.5m. Red clay samples were collected from Kolfe, Addisu Gebeya, Aweliya and Shegole area while those expansive soil samples were collected from Bole, CMC, Emperial Hotel and Hayahulet areas.


Figure 1. 1 Location of the study area

### 1.5. Organization of the thesis

The research report is subdivided in to five Chapters which deal with specific topics in the study. Chapter one deals with background of the problem, objective of the study, methodology, and scope of the study. Literatures in the same study area were reviewed and presented in detail in Chapter two. Laboratory test results and soil classification were presented in Chapter three. Chapter four focus on discussion of laboratory test results which include prediction of SWCC for different samples as well as prediction of unsaturated shear strength parameter $\Phi^b$. Conclusion and recommendation are stated in Chapter five.

# CHAPTER 2

## 2. LITERATURE REVIEW

### 2.1. General

The property of soil strongly depends on the grain size of soils. Soils are classified as cohesive and non-cohesive (granular). The property of granular soils strongly depends on the gravity of forces ( the amount of mass contained in the soils) while the behavior of clay soils strongly depends on surface tension forces, since clays have big specific surface as compared with their mass. The surface tension forces on the other hand are dependent on the mineralogical composition and mineralogical structure of each clay particle. Gravity dependent properties tend to be global, therefore the behavior of granular soils tend to be uniform irrespective of their particular location and condition of formation. Their property is more influenced on their density while the behavior of clayey soils depends on the mineralogical composition and mineralogical structure which is strongly dependent on localized factors such as basic mineralogy, structure, moisture condition, environment etc. (Grim, 1962)

Clay soils are generally defined as soils with grain size less than 0.002mm or 0.005mm depending on which classification system used.

The most important grain-level property of fine grained soil is mineralogical composition. Clay minerals are essentially micro-crystalline, hydrous aluminum (occasionally magnesium or iron) silicates having layered flaky structure. There are two basic structural units. The first structural unit comprises two-layered sheet made up from units of six hydroxyl (or oxygen) ions in octahedral coordination with aluminum, iron or magnesium ions and the second structural unit comprises sheet silicate structure.(Grim, 1962)

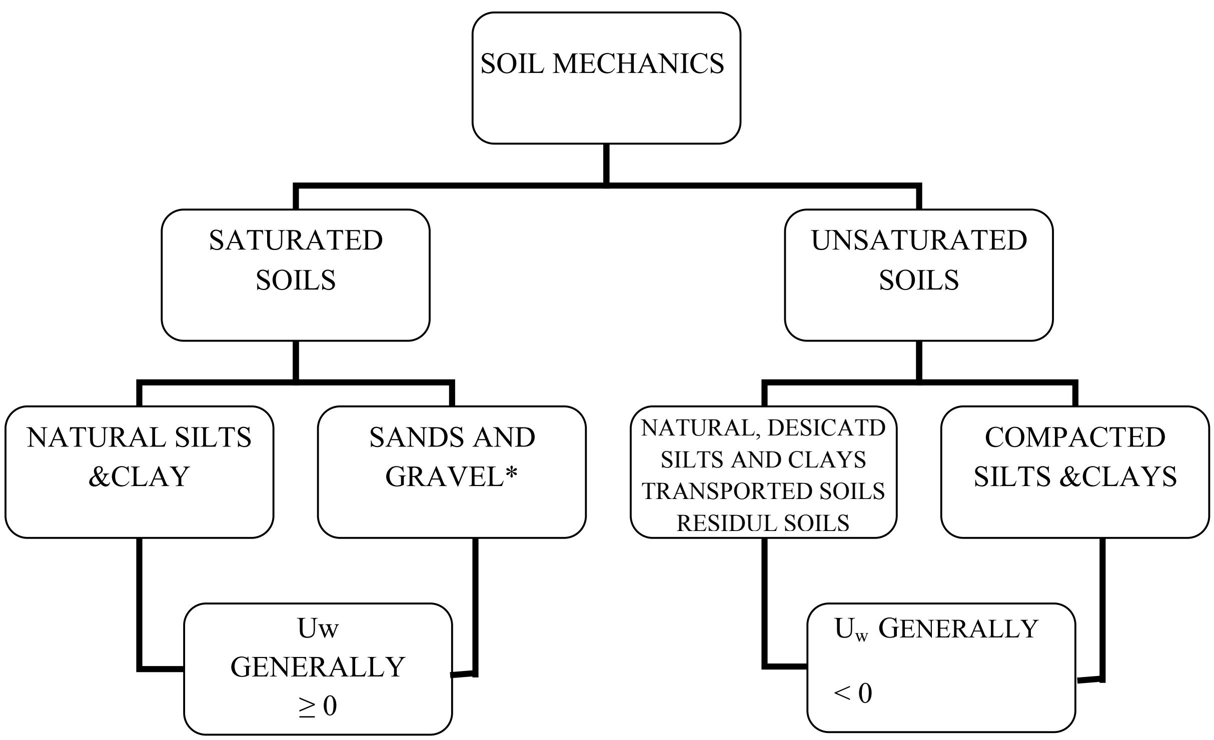
The three most important groups of clay minerals are Montimorillonite, Kaolinite and Illite which are crystalline hydrous alumino-silicates. Montimorillonite is the clay mineral that is present in most of expansive soils, while Kaolinites and Illites dominate in other clay soils. The behavior of clayey soils depends on the amount of clay minerals present, their exchangeable ions, the electrolyte content of the aqueous phase, and internal structure. (Chen, 1975)

The basic building blocks of the clay minerals are the silica tetrahedron and the alumina octahedron. These blocks combine in to tetrahedral and octahedral sheets to produce the various types of clays. (Ralph B. and *et.al* 1974)

## 2.2. Unsaturated soil mechanics

Fredlund and Rahardjo, 1993 stated that the general field of soil mechanics can be subdivided into that portion dealing with saturated soils and that portion dealing with unsaturated soils as shown in figure 2.1. There are numerous materials encountered in engineering practice whose behavior is not consistent with the principles and concepts of classical saturated soil mechanics. Commonly, it is the presence of more than two phases that results in a material that is difficult to deal with in engineering practice. Soils that are unsaturated form the largest category of materials which do not adhere in behavior to classical, saturated soil mechanics.

The differentiation between saturated and unsaturated soils becomes necessary due to basic differences in their nature and engineering behavior. An unsaturated soil has more than two phases, and the pore-water pressure is negative relative to the pore-air pressure. Any soil near the ground surface, present in a relatively dry environment, will be subjected to negative pore-water pressures and possible desaturation. (Fredlund and Rahardjo, 1993)




*May be saturated or dry

Figure 2. 1 Categorization of Soil Mechanics (Fredlund and Rahardjo, 1993)

Unlike the saturated soil mechanics, an unsaturated soil has more than two phases which are commonly known to be solids, water, air and air-water interface or contractile skin. (Fredlund and Morgenstern, 1977)

Climate plays an important role in whether a soil is saturated or unsaturated. Water is removed from the soil either by evaporation from the ground surface or by evapo-transpiration from a vegetative cover as shown in figure 2.2. These processes produce an upward flux of water out of the soil. On the other hand, rainfall and other forms of precipitation provide a downward flux into the soil. The difference between these two flux conditions on a local scale largely dictates the pore-water pressure conditions in the soil. (Fredlund and Rahardjo, 1993)

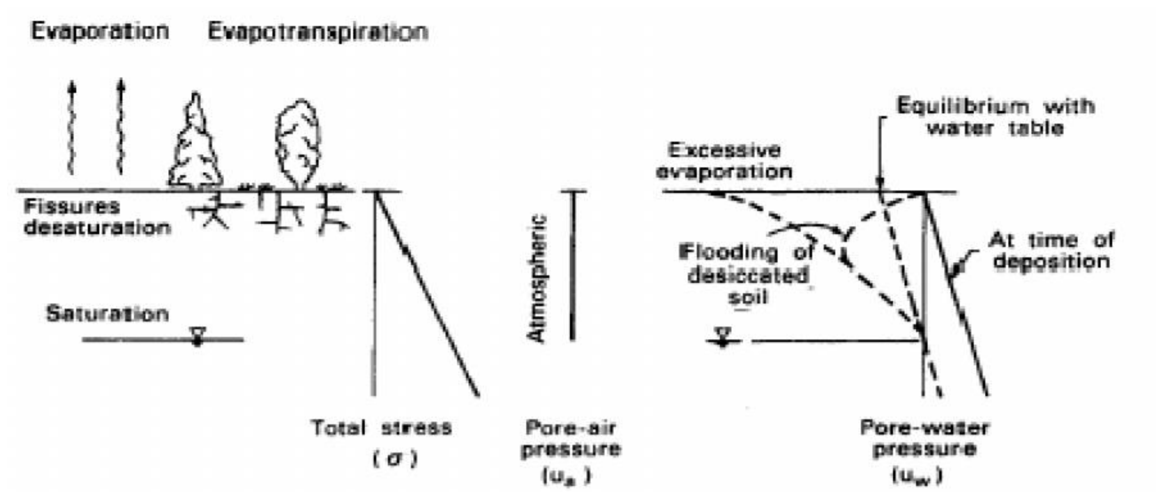



Figure 2. 2 Stress distribution during desiccation of a soil (Fredlund and Rahardjo, 1993)

Fredlund and Rahardjo,1993 stated that a net upward flux produces a gradual drying, cracking, and desiccation of the soil mass, whereas a net downward flux eventually saturates a soil mass. The depth of the water Table is influenced, amongst other things, by the net surface flux. A hydrostatic line relative to the groundwater Table represents an equilibrium condition where there is no flux at ground surface. During dry periods, the pore-water pressures become more negative than those represented by the hydrostatic line. The opposite condition occurs during wet periods.

The size and extent of the near-surface unsaturated soil zone are highly sensitive to disturbance in local or regional climate. Precipitation, evaporation, and evapo-transpiration are all important natural environmental mechanisms that act to influence the depth and extent of the unsaturated zone. Figure 2.3 shows a schematic diagram of the unsaturated soil environment and its role in the natural hydrologic cycle. (Ning and William, 2004)

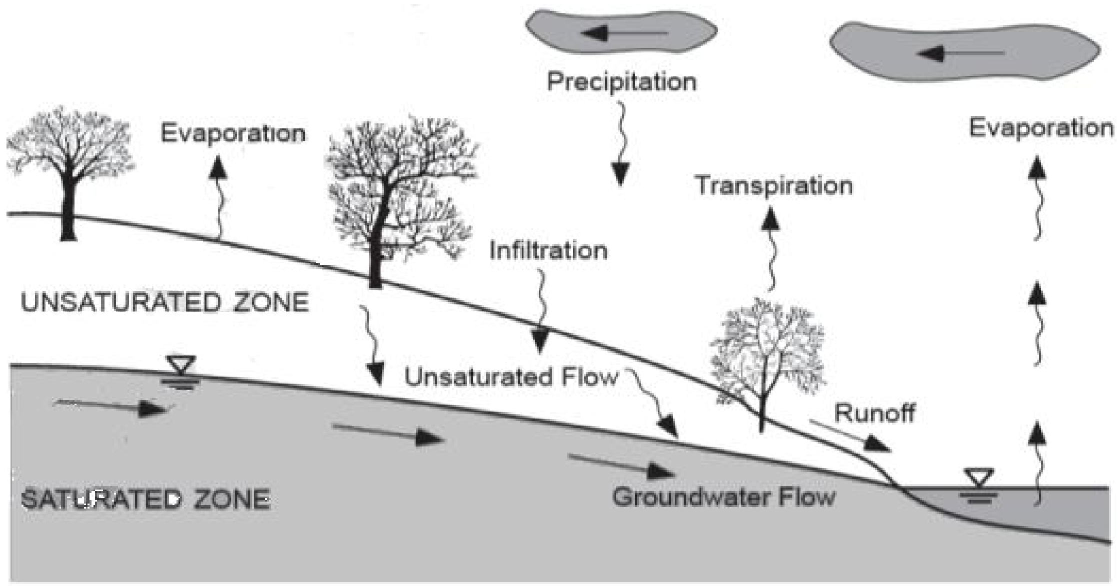



Figure 2. 3 Role of the unsaturated zone in the natural hydrologic cycle (Ning and William, 2004)

### 2.3. Unsaturated soil in engineering practice

For many years, unsaturated soils were either ignored in civil engineering design and construction analyses or were approached inappropriately from the traditional framework of saturated soil mechanics. Rapid advancement in our understanding of unsaturated soil behavior over the last 30 to 40 years, however, has led today's civil engineer to realize that there is now an opportunity to approach problems involving unsaturated soil on a much more rational basis. The expanding knowledge base on the fundamental principles of unsaturated soil mechanics is increasingly being incorporated into a diverse array of practical engineering problems. (Ning and William, 2004)

Common types of engineering problems involving predominantly unsaturated soils include stress related and deformation related problems. Slope stability and land sliding under changing climatic conditions, Lateral earth pressure and stability of retaining structures, Excavation and borehole stability, bearing capacity for shallow foundations under moisture loading and Stress wave propagation in unsaturated soil are among those stress related problems. Swelling and shrinkage of expansive soil, Desiccation cracking of clay, collapsing soil, Soil compaction, Consolidation and settlement of unsaturated soil were among problems related to deformation. (Ning and William, 2004)

Fredlund and Rahardjo, 1993a, stated that unsaturated soil mechanics has become a necessary tool for analyzing the behavior of soils in the vadose zone and the flux boundary conditions as required in many geotechnical and geo-environmental problems.

Classical soil mechanics has emphasized specific types of soils such as saturated sands, Silts, Clays and dry sands. The previous text books cover the theories related to these types of soils in a completely dry or a completely saturated condition. Recently, it has been shown that attention must be given to soils that do not fall in to these common categories. Many of these soils can be classified as unsaturated soils. Engineering related to unsaturated soils has typically remained empirical due to the complexity of their behavior. An unsaturated soil consists of more than two phases and therefore the natural laws governing its behavior are changed. Central to the behavior of an unsaturated soil is the relationship between water and air as the soil desaturates. This relationship is described by the Soil-Water Characteristic Curve (SWCC). Laboratory studies have shown that there is a relationship between the Soil-Water Characteristic Curve and unsaturated soil properties. (Fredlund and Rahardjo, 1993b)

### 2.3.1. Stress in the unsaturated state

Subsurface moisture, suction, and stress profiles depend on the soil and pore-water properties as well as the prevalent environmental or atmospheric conditions. Soil type and pore size distribution all act to influence the equilibrium distribution and flow of pore water within the soil profile. Atmospheric conditions, which include relative humidity, temperature, wind speed, and precipitation, all act to influence transient changes in the flow and distribution of the subsurface pore water.

The mechanical stability of any point in the subsurface depends on the strength parameters of the soil and the state of stress at that point. In saturated soil, the state of stress can be described by total stress and pore pressure, unified under the concept of effective stress. Effective stress, which is the difference between total stress and pore pressure, is the stress experienced by soil's solid phase, or skeleton. The state of effective stress controls whether or not a given soil mass is under a state of stability or a state of failure. Soil strength is an intrinsic material property that generally depends on the soil mineralogy, particle morphology, and inter-particle arrangement.

Macroscopic description of these controlling factors often leads to empirical material parameters, most notably cohesion and internal friction angle. These material parameters, together with the stress state variables, define the boundaries controlling whether soils are in stable or failure conditions.

Total stress can be considered as an external stress and is due to either surcharge load or the soil's self-weight. Pore pressure in saturated soil is generally compressive and isotropic. All pore pressure in saturated soil contributes to total stress according to the effective stress principle. Pore pressure in unsaturated soil, on the other hand, is generally tensile. The contribution of pore pressure to total stress depends on the degree of saturation and pore size distribution. This contribution is not always 100%, making analysis of the state of stress in unsaturated soil far more complicated than the relatively simple case for saturated conditions. (Ning and William, 2004)

### 2.3.2. Shear strength of unsaturated soil

The shear strength of soils is extremely important to foundation design. In addition to this, slopes of all kinds, including hills, river banks and manmade cuts and fills stay in place only because of the shear strength of the material of which they are composed. Knowledge of the shear strength of soil is important for the design of structural foundations, embankments, retaining walls, pavements and cuts. (Nasresh C. and Edward A., 2006)

Shear strength parameters are crucial for stability analyses of slopes against slope failures and landslides. The three shear strength parameters that are required to define a failure envelope of an unsaturated soil are $c'$ (apparent cohesion),$\Phi'$(effective angle of friction) and $\Phi^b$(shear strength change with change in matric suction). A soil-water characteristic curve (SWCC) that relates the water content of a soil to matric suction is another important relationship for the unsaturated soil mechanics. The SWCC essentially shows the ability of an unsaturated soil to retain water under various matric suctions.

When the degree of saturation of a soil is greater than about 85%, saturated soil mechanics principles can be applied. However, when the degree of saturation is less than 85%, it becomes necessary to apply unsaturated soil mechanics principles. The transfer of theory from saturated soil mechanics to unsaturated soil mechanics and vice versa is possible through the use of stress state variables. Stress state variables define the stress condition in a soil and allow the transfer of theory between saturated and unsaturated soil mechanics. The stress state variables for unsaturated soils are net normal stress $(\sigma - u_a)$ and matric suction$(u_a - u_w)$, where $\sigma$ is the total stress, $u_a$ is the pore-air pressure and $u_w$is the pore-water pressure. (Fredlund *and Rahardjo, 1987)*

Soils in an unsaturated state have negative pore-water pressures. The difference between the pore-air pressures, $u_a$, and pore-water pressure, $u_w$, is referred to as matric suction $(u_a - u_w)$. Unlike saturated soils, the mechanical behavior of unsaturated soil depends on two independent stress-state variables. These variables are the stress tensor, $(\sigma - u_a)$ which is referred to as net normal stress, and matric suction $(u_a - u_w)$ (Fredlund and Rahardjo, 1993). Soil behavior is independent of the individual values of $u_a, u_w$ or the total stress $\sigma$ as long as the stress-state variables $(\sigma - u_a)$ and $(u_a - u_w)$ are invariant.(Fredlund and Vanapalli, 2002)

Fredlund et al.(1978) proposed the equation shown below for interpreting the shear strength of unsaturated soils in terms of two independent stress-state variables,$(\sigma - u_a)$ and $(u_a - u_w)$:

$$\tau_{ff} = c' + \left(\sigma_f - u_a\right)_f tan\Phi' + (u_a - u_w)_f tan\Phi^b$$

Where $\tau_{ff}$ is the shear stress on the failure plane at failure, $c'$ is the intercept of the extended Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero (it is also referred to as effective cohesion), $(\sigma_f - u_a)_f$ is the net normal stress state on the failure plane at failure, $u_{af}$ is the pore-air pressure on the failure plane at failure, $\Phi'$ is the angle of internal friction associated with the net normal stress state variable , $(u_a - u_w)_f$ is the matric suction on the failure plane at failure, and $\Phi^b$ is the angle indicating the rate of increase in shear strength relative to the matric suction, $(u_a - u_w)_f$. Figure 2.4 shows shear strength envelope for unsaturated soils. (Fredlund *and Rahardjo, 1993)*

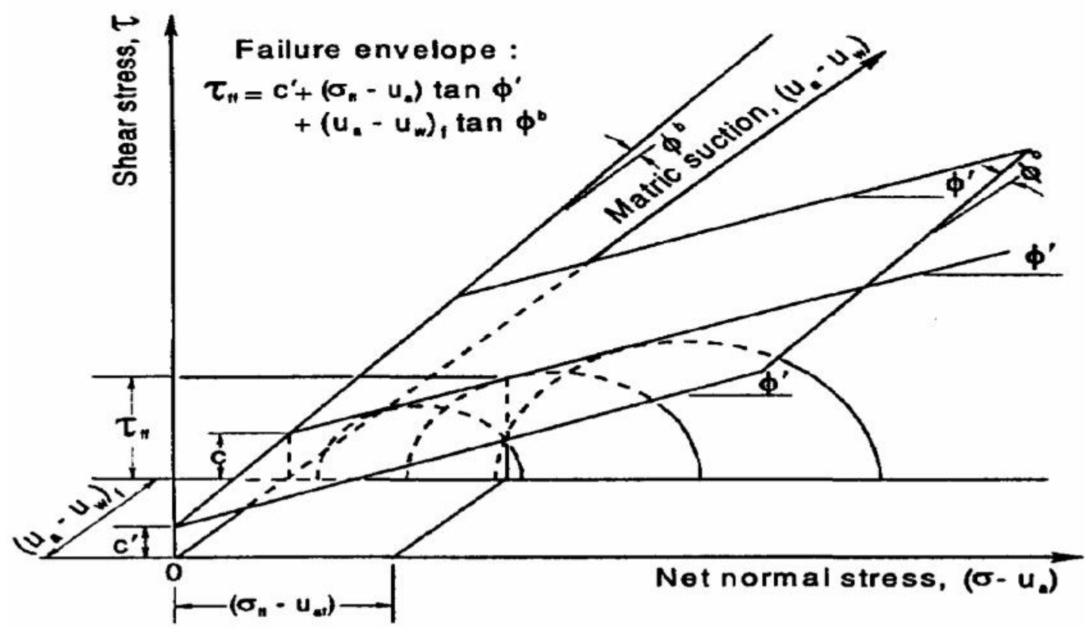


Figure 2. 4 Shear strength envelope for unsaturated soils

## 2.4. Soil water characteristic curve (SWCC)

### 2.4.1. General

The soil-water characteristic curve is a fundamental constitutive relationship in unsaturated soil mechanics. In general terms, the soil-water characteristic curve describes the relationship between soil suction and soil water content. More specifically, the soil-water characteristic curve describes the thermodynamic potential of the soil pore water relative to that of free water as a function of the amount of water adsorbed by the soil system. At relatively low water content, the pore water potential is relatively low compared with free water and the corresponding soil suction is high. At relatively high water content, the difference between the pore water potential and the potential of free water decreases and the corresponding soil suction is relatively low. When the potential of the pore water is equal to the potential of free water, the soil suction is equal to zero. For soil with negligible amount of dissolved solutes, suction approaches zero as the degree of saturation approaches unity. (Ning and William, 2004)

The soil – water characteristics curve (SWCC) defines the relationship between matric suctions (ψ) and water content [gravimetric (w) which is the ratio of mass of water to the mass of solids or volumetric (θ) which is the ratio of volume of water to the total volume of soils or degree of saturation (S) which is the ratio of volume of water to the volume of voids] (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 behavior 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 behavior 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.

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 beyond which it becomes increasingly difficult to remove water from a specimen by drainage. The above mentioned parameters were shown in the following typical SWCC plot.

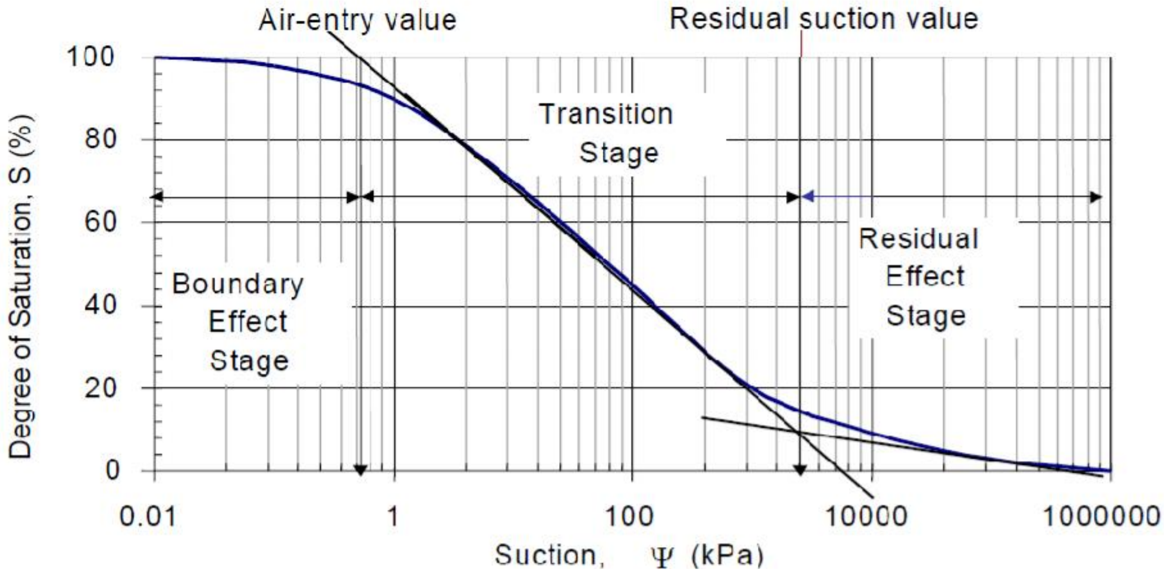



Figure 2. 5 Typical soil-water characteristic curve (SWCC) (Brooks and Corey, 1966)

## 2.4.2. Soil-water characteristic curve models

Numerous empirical equations have been proposed to simulate the soil-water characteristic curve by different researchers. The model developed by Brooks and Corey (1964), Van Genuchten (1980) and Fredlund and Xing (1994) were among the commonly used ones.

### 2.4.2.1. Brooks-Corey model

One of the earliest approaches for modeling the soil-water characteristic curve is an equation proposed by Brooks and Corey (1964). Based on observations from a large set of experimental suction and water content measurements, Brooks and Corey proposed a two-part power law relationship incorporating a ‘‘pore size distribution index, λ’’. The model is non smooth or open form about the air-entry pressure, $\psi_b$, and is written as:

$$\Theta = S = \begin{cases} 1 & \psi_b < \psi \\ \left(\frac{\psi_b}{\psi}\right)^{\lambda} & \psi_b > \psi \end{cases} \quad \text{(2.1)}$$

where:- S=Degree of saturation, Θ=Normalized water content, $\psi_b$= air entry pressure, $\psi$ = matric suction, $\lambda$ = pore size distribution index

Ning and William, 2004 stated that the Brook-Corey model is most appropriate for relatively coarse-grained soils where drainage occurs over a relatively low and relatively narrow range that the model tends to lose applicability at high suctions approaching the residual water content. The absence of an inflection point in the form of the model often results in poor representation of the SWCC over a wide suction range. The non smoothness occurring at the air-entry pressure leads to a sharp discontinuity in the specific moisture capacity and hydraulic diffusivity functions which can often lead to numerical instability when modeling fluid flow behavior near saturation.

#### 2.4.2.2. Van Genuchten (VG) Model

Van Genuchten, (1980) proposed a smooth, closed-form, three-parameter model for the soil-water characteristic curve in the form:

$$\Theta = S = \left(\frac{1}{1+(a\psi)^n}\right)^m \text{------------------------------------------------------------------------------------ (2.2)}$$

Where *a*, *n*, and *m* are curve fitting parameters while $\psi$ is matric suction and S is degree of saturation.

The suction term appearing on the right-hand side of eq.(2.2) may be expressed in either units of pressure (i.e. $\psi$ =kPa, as shown) or head (i.e.=m). In the former case, '*a*' parameter is designated more specifically as '$\alpha$' and has inverse units of pressure (1/kPa). In the latter case, '*a*' parameter is designated as '$\beta$' and has inverse units of head (1/m). Both '$\alpha$' and '$\beta$' are related to the air-entry condition, where '$\alpha$' approximates the inverse of the air-entry pressure, and '$\beta$' approximates the inverse of the air-entry head or the height of the capillary fringe. The *n* parameter is related to the pore size distribution of the soil and the *m* parameter is related to the overall symmetry of the characteristic curve. The *m* parameter is frequently constrained by direct relation to the *n* parameter as:

$$m = 1 - \frac{1}{n} \quad \text{or} \quad m = 1 - \frac{1}{2n} \text{-----------------------------------(2.3)}$$

Ning and William, 2004 stated that the mathematical form of the VG model, which accounts for an inflection point, allows greater flexibility than the Brook-Corey model over a wider range of suction and better captures the sigmoidal shape of typical curves. Smooth transitions at the air-entry pressure and for suction approaching the residual condition are more effectively captured.

#### 2.4.2.3. Fredlund and Xing (FX) Model

Fredlund and Xing (1994) developed a model based on consideration of pore size distribution in a form similar to the VG model as

$$\theta = C(\psi)\theta_s \left[\frac{1}{ln\left[e+(\frac{\psi}{a})^n\right]}\right]^m \text{------------------------------------------- (2.4)}$$

where $\psi$ is suction (kPa), *a*, *n*, and *m* are curve fitting parameters, *e* is the natural logarithmic constant, and $C(\psi)$ is a correction factor that forces the model through a prescribed suction value of $10^6$kPa at zero water content.

$$C(\psi) = \left[1 - \frac{\ln(1+\psi/\psi_r}{\ln(1+10^6/\psi_r}\right]$$

According to Ning and William, 2004 comparison with experimental data indicates that the FX model is capable of describing well the characteristic curves over the range of suction from 0 kPa all the way to $10^6$kPa.

Perera and *et.al, 2005* have developed a correlation between the Fredlund and Xing fitting parameters and simple index properties along with grain size distribution (GSD) by conducting tests on numerous plastic and non-plastic soils. The four fitting parameters were correlated to the parameters derived from GSD and PI. To develop the correlation equations 154 non-plastic and 63 plastic soil samples test results have been used. They developed two sets of correlations equations for non-plastic soils and plastic soils.

$$S = C(h) * \left[\frac{1}{\left[ln\left[\exp(1)+\left(\frac{h}{a_f}\right)^{b_f}\right]\right]^{c_f}}\right] \text{------------------------------------------- (2.5)}$$

Where, $C(h) = \left[1 - \frac{\ln\left(1+\frac{h}{h_{rf}}\right)}{\ln\left(1+\frac{10^6}{h_{rf}}\right)}\right]$

$S$ = Degree of saturation

$h$ = matric suction in kPa,

$a_f$ = Curve fitting parameter, which is primarily a function of the air entry value of the soil,

$b_f$= Curve fitting parameter, which is primarily a function of the rate of water extraction from the soil, once the air entry value has been exceeded,

$c_f$= Curve fitting parameter, which is primarily a function of the residual water content,

$h_{rf}$= Curve fitting parameter, which is primarily a function of the suction at which residual water content occurs, and

$C(h)$= correction factor which is a function of matric suction

***<u>Correlation Equations for Non-Plastic Soils</u>***

$a_f = 1.14a - 0.5$------------------------------------------------------------------------------------------ (2.6)

Where: $a = -2.79 - 14.1\log(D_{20}) - 1.9x10^{-6}P_{200}^{4.34} + 7\log(D_{30}) + 0.055D_{100}$

$D_{100} = 10^{\left[\frac{40}{m_1}+\log(D_{60})\right]}$ , $m_1 = \frac{30}{[\log(D_{90})-\log(D_{60})]}$

**Note**: Some extreme cases may exist where the computed value of $a_f$ is negative, which will lead to erroneous results. Therefore, the value of $a_f$ has been limited to 1.0.

$b_f = 0.936b - 3.8$------------------------------------------------------------------------------------- (2.7)

Where: $b = \left\{5.39 - 0.29ln\left[P_{200}\left(\frac{D_{90}}{D_{10}}\right)\right] + 3D_0^{0.57} + 0.021P_{200}^{1.19}\right\}m_1^{0.1}$

$D_0 = 10^{\left[\frac{-30}{m_2}+\log(D_{30})\right]}$ , $m_2 = \frac{20}{[\log(D_{30})-\log(D_{10})]}$

$C_f = 0.26e^{0.78c} + 1.4D_{10}$----------------------------------------------------------------------------- (2.8)

Where: $C = log(m_2^{1.15}) - \left(1 - \frac{1}{b_f}\right)$

$h_{rf}$ = 100------------------------------------------------------------------------------------------------ (2.9)

***<u>Correlation Equations for Plastic Soils</u>***

$a_f = 32.835\{ln(wPI)\} + 32.438$--------------------------------------------------------------------- (2.10)

$b_f = 1.421(wPI)^{-0.3185}$-------------------------------------------------------------------------------- (2.11)

$C_f = -0.2154\{ln(wPI)\} + 0.7145$------------------------------------------------------------------- (2.12)

$h_{rf}$ = 500------------------------------------------------------------------------------------------------ (2.13)

wPI= Weighed Plasticity index is the product of $P_{200}$ (expressed as a decimal) and the PI.

Grain size distribution (GSD) of a soil is closely related to its pore size distribution. Hence, the GSD holds a close relation with the SWCC. In addition to the GSD, the plasticity index is the measure of water holding capacity of a soil. This implies that it plays an important role in shaping the SWCC. Therefore weighted plasticity index (wPI) which is a product of P200 from GSD and PI has an effect on shaping the SWCC. (Perera and *et.al* 2005)

Perera and *et.al* 2005 stated that, the above correlation equations are useful in predicting the SWCC of any given soil without carrying out actual SWCC testing and can be used to solve various unsaturated soil mechanics problems. The correlation equations for Plastic soils can be used for plastic soil samples whereas those correlation equations for non plastic soils can be used for non plastic soil samples.

Table 2. 1 Some Common Empirical Equations Used to Best-Fit SWCC Data (Fredlund, 2006)

| References | Equations | Description |
|---|---|---|
| Gardner (1958) | $\Theta_n = \frac{1}{1 + \frac{1}{a_g}\psi^{n_g}}$ | $a_g$ =soil parameter which is primarily a function of the air entry value of the soil and $n_g$ =soil parameter which is primarily a function of the rate of water extraction from the soil, once the air entry value of the soil has been exceeded. |
| Brooks and Corey (1964) | $\Theta_n = 1, \quad \psi \leq \psi_{aev}$<br>$\Theta_n = \left(\frac{\psi}{\psi_{aev}}\right)^{-\lambda_{bc}}, \quad \psi \geq \psi_{aev}$ | $\psi_{aev}$ =air entry value of the soil and $\lambda_{bc}$ =pore size distribution index. $\psi$ = matric suction |
| Brutsaert (1967) | $\Theta_n = \frac{1}{1 + \left(\frac{\psi}{a_b}\right)^{n_b}}$ | $a_b$ =soil parameter which is primarily a function of the air entry value of the soil and $n_b$ =soil parameter which is primarily a function of the rate of water extraction from the soil, once the air entry value has been exceeded. |
| Laliberte (1969) | $\Theta_n = \frac{1}{2} erfc\left[a_1 - \frac{b_1}{c_1 + \left(\frac{\psi}{\psi_{aev}}\right)}\right]$ | The parameters $a_1$, $b_1$, and $c_1$ are assumed to be unique functions of the pore-size distribution index. |
| Farrel and Larson (1972) | $w = w_s - \frac{1}{\alpha_f} ln \frac{\psi}{\psi_{aev}}$ | $\alpha_f$ = pore-size distribution index medium parameter, $w_s$ = gravimetric water content at saturation |
| Cambell (1974) | $w = w_s \left(\frac{\psi}{\psi_{aev}}\right)^{-1/b_c}, \quad \psi \geq \psi_{aev}$<br>$w = w_s, \quad \psi < \psi_{aev}$ | $\psi_{aev}$ =air entry value of the soil and $b_c$ =a constant. |

| | | |
|---|---|---|
| Van Genuchten (1980 | $\Theta_n = \frac{1}{\left[1+\left(\frac{\psi}{a_v}\right)^{n_v}\right]^{m_v}}$, $m_v = 1 - \frac{1}{n_v}$ or $m_v = 1 - \frac{2}{n_v}$ | $a_v$=soil parameter which is primarily a function of air entry value of the soil (1/kPa); $n_v$=soil parameter which is primarily a function of the rate of water extraction from the soil, once the air entry value has been exceeded; and $m_v$=soil parameter which is primarily a function of the residual water content. |
| McKee and Bumb (1987) | $\Theta_n = \frac{1}{1+\exp\left(\frac{\psi - a_n}{n_m}\right)}$ | $a_n$ and $n_m$ = curve fitting parameters |
| Fredlund and Xing (1994) | $w(\psi) = C(\psi)\frac{w_s}{\left\{\ln\left[e+\left(\frac{\psi}{a_f}\right)^{n_f}\right]\right\}^{m_f}}$ $C(\psi) = 1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left[1+\left(\frac{10^6}{\psi_r}\right)\right]}$ | $a_f$=soil parameter which is primarily a function of the air entry value of the soil; $n_f$=soil parameter which is primarily a function of the rate of water extraction from the soil, once the air entry value has been exceeded; $m_f$=soil parameter which is primarily a function of residual water content; and $C(\psi)$=correction which is primarily a function of the suction at which residual water content occurs. |
| Feng and Fredlund (1999) hysteresis model | $w(\psi) = \frac{ab + c\psi^d}{b + \psi^d}$ | *a*=ceramic water content at suction is equal to 0 on the main loop and *c*=ceramic water content when the ceramic tip is in dry condition; with one branch of the main hysteresis loop measured, only two parameters *b*, and *d*, remain unknown for the other branch. |

Note: $\Theta_n$= (*w−wr)* / (*ws−wr)* =normalized water content; *w*=any gravimetric water content; *wr*=residual gravimetric water content; *ws*=gravimetric water content at saturation; $\Theta$ =*w*/*ws*=dimensionless water content; *ws* and *wr*=saturation and residual gravimetric water contents, respectively; and ψ =soil suction.

### 2.4.3. Need for developing soil water characteristic curve (SWCC) models

Bringing unsaturated soil mechanics in to practice was difficult due to the problems associated with testing mechanism. Testing of unsaturated soil involves complex testing procedures which is not practicable for the practicing engineer. The problem is not only the complexity of the testing procedure. The expensiveness of the equipment and time consuming testing was also among the constraints. To solve the aforementioned problems many researchers in the field has tried to simplify the difficulty associated with testing mechanism by developing soil water characteristic models which can be correlated with simple index properties of soils.

The measurement of soil parameters for the unsaturated soil constitutive models remains demanding laboratory process. For most practical problems approximate soil properties are adequate for analysis purpose. Hence, empirical procedures to estimate unsaturated soil parameters are sufficient. (Fredlund and *et.al,* 1995)

Fredlund, 2006 stated that one of the main obstacle standing in the way of implementation of unsaturated soil mechanics has been the excessive cost and demanding laboratory testing techniques associated with the direct experimental assessment of unsaturated soil properties. Since the unsaturated soil properties are functions of the stress state, it is necessary to make a series of soil property measurements on a particular soil. These measurements must be made under controlled stress states that involve both total stresses and matric suction. The equipment required to measure the unsaturated soil property functions becomes costly and demanding; thus making its usage unacceptable for most routine engineering applications. Consequently, the need arises for practical solutions for the determination of unsaturated soil property function. Soil–water characteristic curves have emerged as a practical and sufficient estimation tool for obtaining unsaturated soil property functions.

The current technology to develop numerical models far exceeds our ability to measure the properties of an unsaturated soil. The measurement of the properties of unsaturated soils is costly and time consuming. Estimates of these properties using empirical procedures may be sufficient for most applications. The soil-water characteristic curve is fundamental relationship of unsaturated soils which provides a conceptual and interpretive tool by which the behavior of unsaturated soils can be understood. As the soil moves from a saturated state to dry conditions, the distribution of the soil-water-air phases changes as the stress state changes. It is the interactions between these phases and the distribution of these phases (i.e. volume, geometry and continuity) that control unsaturated soil properties. (S.Vanapalli and *et.al* , 1996)

### 2.4.4. Prediction of unsaturated shear strength parameter, $\Phi^b$

Fredlund and *et.al* (1978) have proposed a relationship to explain the shear strength of unsaturated soils in terms two independent stress state variables as shown below:

$$\tau_f = C' + (\sigma_n - u_a)tan\phi' + (u_a - u_w)tan\Phi^b \qquad (2.14)$$

Where: $\tau_f$ = Shear strength of unsaturated soil

C'= Effective cohesion

$\phi'$= Effective angle of frictional resistance for a saturated soil

$\Phi^b$= Angle of frictional resistance with respect to soil suction

$\sigma_n - u_a$= Net normal stress

$u_a$= Pore air pressure

Vanapalli et al. (1996) and Fredlund et al. (1996) have proposed a function for predicting the shear strength of an unsaturated soil using the entire SWCC (i.e., 0 to 1,000,000 kPa) and the saturated shear strength parameters as shown in equation (2.15) below.

$$\tau = [C' + (\sigma_n - u_a)tan\phi'] + [(u_a - u_w)\{\Theta^K tan\Phi'\}] \qquad (2.15)$$

Where: κ= Curve fitting parameter used for obtaining a best-fit

It is a fitting parameter used to account for non-linearity between area and volume representation of the amount of water contributing to the shear strength.

Θ= S normalized water content, $\theta_w / \theta_s$ $\quad tan\Phi^b = \Theta^\kappa tan\Phi'$

N.B The normalized volumetric water, Θ, is also equal to degree of saturation, S.

The first part of equation (2.15) is the saturated shear strength when the pore-air pressure, $u_a$, is equal to the pore-water pressure, $u_w$. This part of equation is a function of normal stress since the shear strength parameters $c'$ and $\phi'$ is constant for a saturated soil.

For a particular net normal stress, this value is a constant. The second part of the equation is the shear strength contribution due to suction, which can be predicted using the soil water characteristic curve.

Garven and Vanapalli, 2006 proposed a correlation between fitting parameter κ and plasticity index as follows:

$$\kappa = 1.0 + 0.0975 I_P - 0.0016 I_P^2 \qquad (2.16)$$

## 2.5. Laboratory soil tests used to predict soil water characteristic curve (SWCC) of soil

### 2.5.1. Grain size analysis

This test is performed in two stages: sieve analysis for coarse-grained soils (sands, gravels) and hydrometer analysis for fine-grained soils (clays, silts). Soils containing both types are tested in sequence, with soil samples retained on sieve No. 200 by using a set of sieves while those materials passing the No. 200 sieve (0.075 mm or smaller) are analyzed by hydrometer.

#### 2.5.1.1. Sieve Analysis

This test provides a direct measurement of the particle size distribution of a soil by causing the sample to pass through a series of wire screens with progressively smaller openings of known size. The amount of material retained on each sieve is weighed and recorded.

#### 2.5.1.2. Hydrometer Analysis

This test is based on Stokes Law. The diameter of a soil particle is defined as the diameter of a sphere which has the same unit mass and which falls at the same velocity as the particle. Thus, a particle size distribution is obtained by using a hydrometer to measure the change in specific gravity of a soil-water suspension as soil particles settle out over time. Results are reported on a combined grain size distribution plot as the percentage of sample smaller than, by weight, versus the log of the particle diameter. These data are necessary for a complete classification of the soil.

The curve also provides other parameters, such as effective diameter ($D_{10}$) and coefficient of uniformity ($C_u$). Tests shall be performed in accordance with ASTM D 422.

For the prediction of SWCC the percentage of soils finer than sieve No 200 is needed to be accurately determined. In order to determine the percentage of soils finer than sieve No 200 accurately ASTM D-1140-97 was used.

A specimen of the soil is washed over a 75-µm (No.200) sieve. Clay and other particles that are dispersed by the wash water, as well as water soluble materials, are removed from soil during the test. The loss in mass resulting from the wash treatment is calculated as mass percent of the original sample and is reported as percentage of material finer than 75-µm (No.200) sieve by washing.

The amount of material passing the 75-µm (No.200) sieve by washing will be calculated using the following formula:

$$A = [(B - C)/B]X100$$

Where:

A= Percentage of material finer than the 75-µm (No.200) sieve by washing (P200),

B= Original dry mass of sample, g, and

C= Dry mass of specimen retained on the 75-µm (No.200) sieve including the amount retained on an upper sieve after washing, g.

### 2.5.2. Atterberg limit test

In addition to the input value from the grain size analysis, the plasticity index (PI) of the soil sample is required in order to predict the SWCC. Plasticity index (PI) was obtained by conducting Atterberg limit test as per ASTM D-4318 standard.

The liquid limit, plastic limit and shrinkage limit are all Atterberg Limits. However, for classification purposes, the term Atterberg Limits generally refers to the liquid and plastic limits only. The liquid limit (LL) is the moisture content of a soil at the boundary between the liquid and plastic states. The plastic limit (PL) is the moisture content at the boundary between the plastic and semi-solid states. The plasticity index (PI) is the difference between the LL and PL. These values are useful in soil classification and have been correlated with other parameters.

#### 2.5.2.1. Liquid limit

The sample is processed to remove any material retained on a 425-µm (No.40) sieve. The liquid limit is determined by performing trials in which a portion of the sample is spread in a brass cup, divided in two by a grooving tool, and then allowed to flow together from the shocks caused by repeatedly dropping the cup in a standard mechanical device. There are two methods to determine the liquid limit of the soil. The first one is which is known as multipoint liquid limit, Method A, requires three or more trials over a range of water contents to be performed and the data from the trials plotted or calculated to make a relationship from which the liquid limit is determined. The second one is the one-point liquid limit, Method B, which uses the data from two trials at one-water content multiplied by a correction factor to determine the liquid limit. For this thesis the multipoint point liquid limit method was adopted for better accuracy.

#### 2.5.2.2. Plastic limit

Similar to the liquid limit the plastic limit test is also done on samples passing sieve no. 40. The plastic limit is determined by alternatively pressing together and rolling into a 3.2mm (1/8-in.) diameter thread a small portion of plastic soil until its water content is reduced to a point at which the thread crumbles and can no longer be pressed together and rerolled. The water content of the soil at this point is reported as the plastic limit.

The plasticity index is calculated as the difference between the liquid limit and the plastic limit.

$$PI = LL - PL$$

# CHAPTER 3

## 3. LABORATORY TESTS AND RESULTS

### 3.1. General

Soil samples were collected from different known areas within the study area. Red clay samples were collected from Kolfe, Addisu Gebeya, Aweliya and Shegole area while expansive soil samples were collected from Bole, CMC, Emperial Hotel and Hayahulet areas. One test pit was opened at each site and samples were collected from two depths at 1.5m and 2.5m. Different tests were run on the collected samples based on the ASTM requirement for each tests.

### 3.2. Grain size analysis

Percentage of soils finer than 75-µm (No.200) sieve was obtained by running test as per ASTM designation D1140-97 method A for red clay samples and method B for expansive soil samples. Summary of the test results for percentage of soils finer than sieve No. 200(P200) were tabulated in the Table 3.1. Hydrometer analysis was done as per ASTM designation D422-63 and the obtained results were presented on appendix.

### 3.3. Atterberg Limits test

Liquid limit and plastic limit tests were done according to ASTM designation D4318-98. Soil samples passing 425µm sieve were used for Atterberg limits determination. Cassagrande's apparatus was used for the determination of liquid limit. For the determination of plastic limit a soil sample was rolled in to about 3mm thread until it begins to crumble. The results of Atterberg limits are summarized and tabulated in Table 3.1. The detail laboratory test result was presented in appendix A.

### 3.4. Specific gravity

Specific gravity test which is the ratio of the mass of a unit volume of a material at a stated temperature to the mass of the same volume of gas-free distilled water at a stated temperature was done according to ASTM D854-98. The specific gravity of the eight test pits are determined and summarized in Table 3.1.

### 3.5. Free swell tests

Swelling tendency was also determined from the samples passing 425µm sieve and oven dried. The 10ml of soil sample was put in water for 24 hours and swelling was examined as percentage of volume change to the original volume. The results obtained for samples from each test pit are summarized in Table 3.1.

Table 3. 1 Summary of laboratory test results

| Site | Depth | LL (%) | PL (%) | PI (%) | P200 (%) | WPI(%) | Gs | Free Swell,% |
|---|---|---|---|---|---|---|---|---|
| Kolfe | 1.5m | 73.43 | 31.13 | 42.3 | 99.08 | 41.91 | 2.78 | 40.5 |
| | 2.5m | 66.21 | 29.68 | 36.53 | 98.64 | 36.03 | 2.75 | 42.5 |
| Addisu G. | 1.5m | 71.95 | 29.61 | 42.34 | 97.78 | 41.40 | 2.74 | 44 |
| | 2.5m | 72.75 | 32.91 | 39.84 | 97.51 | 38.85 | 2.72 | 46.5 |
| Aweliya | 1.5m | 63.67 | 30.7 | 32.97 | 94.18 | 31.05 | 2.73 | 22 |
| | 2.5m | 64.38 | 30.75 | 33.63 | 93.15 | 31.33 | 2.69 | 15 |
| Shegole | 1.5m | 66.99 | 30.8 | 36.19 | 98.06 | 35.49 | 2.81 | 45 |
| | 2.5m | 70.66 | 31.1 | 39.56 | 96.87 | 38.32 | 2.79 | 65 |
| Bole | 1.5m | 98.68 | 37.9 | 60.78 | 98.83 | 60.07 | 2.64 | 155 |
| | 2.5m | 102.58 | 40.4 | 62.18 | 99.81 | 62.06 | 2.51 | 175 |
| CMC | 1.5m | 103.78 | 42.91 | 60.87 | 94.27 | 57.38 | 2.72 | 135 |
| | 2.5m | 112.03 | 41.88 | 70.15 | 96.59 | 67.76 | 2.73 | 205 |
| Emperial | 1.5m | 102.8 | 38.31 | 64.49 | 95.59 | 61.65 | 2.54 | 95 |
| | 2.5m | 105.53 | 39.59 | 65.94 | 97.23 | 64.11 | 2.47 | 90 |
| Hayahulet | 1.5m | 95.8 | 37.91 | 57.89 | 98.46 | 57.00 | 2.65 | 185 |
| | 2.5m | 93.3 | 37.56 | 55.74 | 92.65 | 51.64 | 2.68 | 165 |

Table 3. 2 Summary of grain size distribution

| Site | % Sand | %Silt | % Clay |
|---|---|---|---|
| Kolfe | 1.36 | 21.20 | 77.44 |
| Addisu G. | 2.49 | 30.14 | 67.37 |
| Aweliya | 6.85 | 15.22 | 77.93 |
| Shegole | 3.13 | 20.52 | 76.35 |
| Bole | 0.19 | 14.24 | 85.57 |
| Emperial | 2.77 | 27.33 | 69.90 |
| CMC | 7.35 | 12.55 | 80.10 |
| Hayahulet-22 | 3.41 | 26.51 | 70.08 |

### 3.6. Soil classification

The soil under investigation was classified based on unified soil classification system. Unified soil classification system (USCS) uses grain size and Atterberg limit test results together to classify the soil. Based on Tables 3.1 and 3.2, one can see that both clay fraction and LL for all samples are greater than 50%, hence, according to USCS all samples can be classified as CH (inorganic fat clay). Moreover, using those test results the plasticity chart was prepared for the soils under investigation. As it can be seen from the plasticity chart below, all samples fall above and on "A-Line" and are grouped under the CH (inorganic fat clay) group.

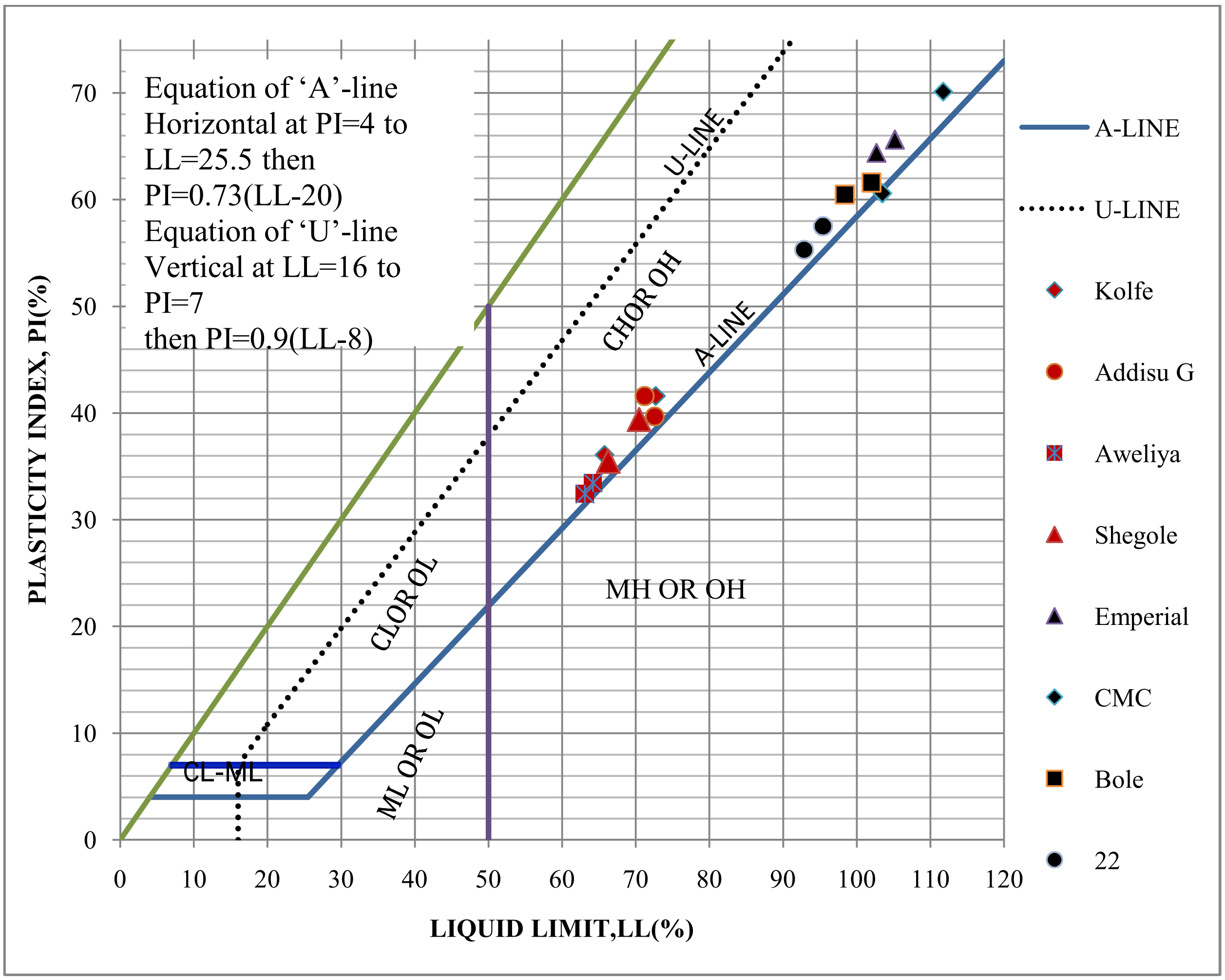



Figure 3. 1 Plasticity chart according to USCS of soil samples under investigation

# CHAPTER 4

## 4. DISCUSSION OF TEST RESULTS

### 4.1. Prediction of Soil water characteristic curve (SWCC)

The soil-water characteristic curve (SWCC) of the samples were predicted using the predictive model developed by Fredlund and Xing 1994 in conjunction with the correlation equations developed by Perera and *et.al 2005* for the fitting parameters as discussed in Chapter two in the literature review section. In the figures 4.1 to 4.5 the SWCC of red clay samples were plotted together with that of the upper and lower limit of Zapata's family of curves for plastic soils. As it can be seen from the plots, the predicted SWCC for all red clay samples falls out of the band of Zapata's family of curves but within the near vicinity of the upper limit. Only Zapata's families of curves were used for comparison as other models do not have specific empirical relationship for the fitting parameters.

**<u>SWCC Curve for Kolfe Site</u>**

In order to plot the SWCC data's obtained from laboratory test result in conjunction with the equations provided in Chapter two were used.

$$S = C(h) * \left[ \frac{1}{\left[ ln\left[ \exp(1) + \left(\frac{h}{a_f}\right)^{b_f} \right] \right]^{c_f}} \right] - - - - - - - - - - - - - - - - - - - eqn(2.5)$$

Data's from laboratory test result:

| Site | LL (%) | PL (%) | PI (%) | P200 | wPI | Φ' |
|---|---|---|---|---|---|---|
| Kolfe | 66.21 | 29.68 | 36.53 | 0.9864 | 36.03 | 21° |
| | $a_f$ | $b_f$ | $c_f$ | $h_{rf}$ | $\kappa$ | |
| | 150.13 | 0.45 | -0.058 | 500 | 2.43 | |

To Compute $a_f$

$$w_{PI} = P_{200}\ x\ PI = 36.03$$

$$a_f = 32.835\{ln(wPI)\} + 32.438 = 150.13$$

$b_f = 1.421(wPI)^{-0.3185} = 0.45$

$C_f = -0.2154\{ln(wPI)\} + 0.7145 = -0.058$

$h_{rf} = 500$

$\kappa = 1.0 + 0.0975 I_P - 0.0016 I_P^2 = 2.43$

for h=100 kPa and $h_{rf} = 500$

$$C(h) = \left[1 - \frac{\ln\left(1 + \frac{h}{h_{rf}}\right)}{\ln\left(1 + \frac{10^6}{h_{rf}}\right)}\right] = \left[1 - \frac{\ln\left(1 + \frac{100}{500}\right)}{\ln\left(1 + \frac{10^6}{500}\right)}\right] = 0.98$$

$$S = C(h) * \left[\frac{1}{\left[ln\left[\exp(1) + \left(\frac{h}{a_f}\right)^{b_f}\right]\right]^{c_f}}\right] = 0.98 \left[\frac{1}{\left[ln\left[\exp(1) + \left(\frac{100}{150.13}\right)^{0.45}\right]\right]^{-0.058}}\right] \cdot \frac{100}{100}$$

$= 98.94\%$

In similar manner degree of saturation was computed for different values of matric suction.

The predicted unsaturated shear strength parameter $\Phi^b$ was also computed as follows:-

$tan\Phi^b = \Theta^{\kappa} tan\Phi'$, where, $\Theta = S$, $\Phi^b = \arctan(\Theta^{\kappa} tan\Phi')$, for h=100kPa, $\kappa = 2.43$

S= $\Theta$=98.94%=0.9894, Φ'(from Getaneh, 2010)=21°,

$\Phi^b = \arctan(\Theta^{\kappa} tan\Phi') = 20.51°$

| h (kPa) | C(h) | S (%) | $\Phi^{bp}$ |
|---|---|---|---|
| 0.01 | 1.00 | 100.03 | 21.01 |
| 16.75 | 1.00 | 100.26 | 21.12 |
| 36.67 | 0.99 | 100.00 | 21.00 |
| 50.2 | 0.99 | 99.79 | 20.90 |
| 100 | 0.98 | 98.94 | 20.51 |
| 500 | 0.91 | 93.00 | 17.84 |
| 2500 | 0.76 | 79.16 | 12.28 |
| 12500 | 0.57 | 59.97 | 6.33 |
| 62500 | 0.36 | 38.68 | 2.19 |
| 312500 | 0.15 | 16.44 | 0.28 |
| 1000000 | 0.00 | 0.00 | 0.00 |

Using the above tabulated values SWCC for Kolfe Site was plotted in figure 4.1(S (Degree of Saturation Vs h (Matric Suction). SWCC for other samples were also computed in similar manner and tabulated in Appendix.

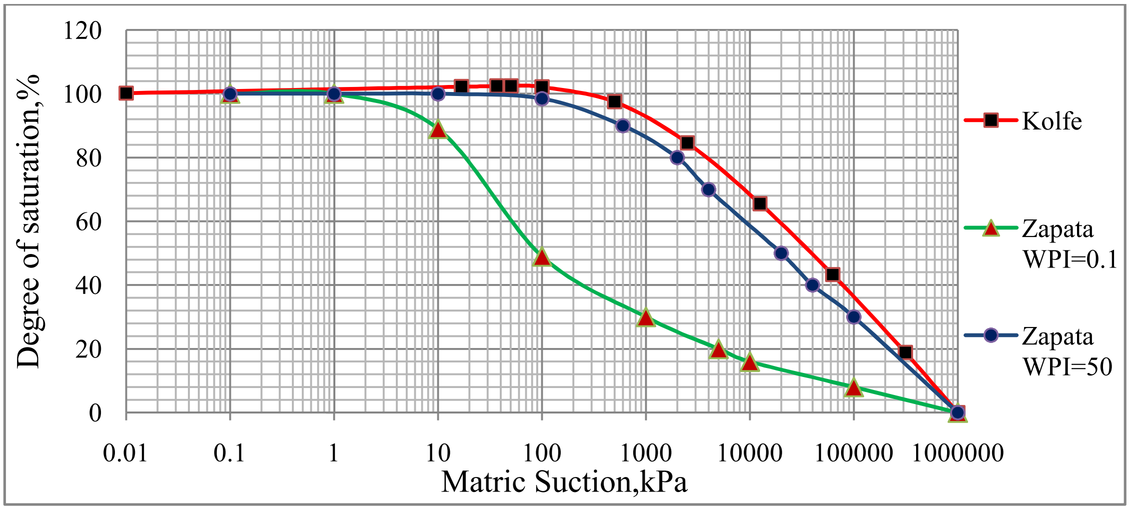



Figure 4. 1 Soil-water characteristic curves for Kolfe site along with Zapata's upper and lower limit for plastic soils

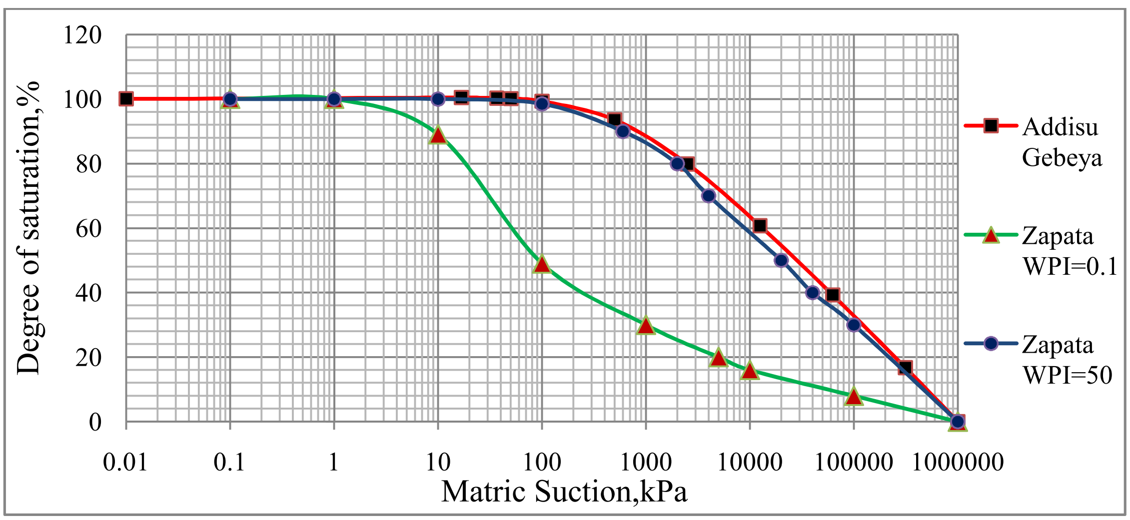



Figure 4. 2 Soil-water characteristic curves for Addisu Gebeya site along with Zapata's upper and lower limit for plastic soils

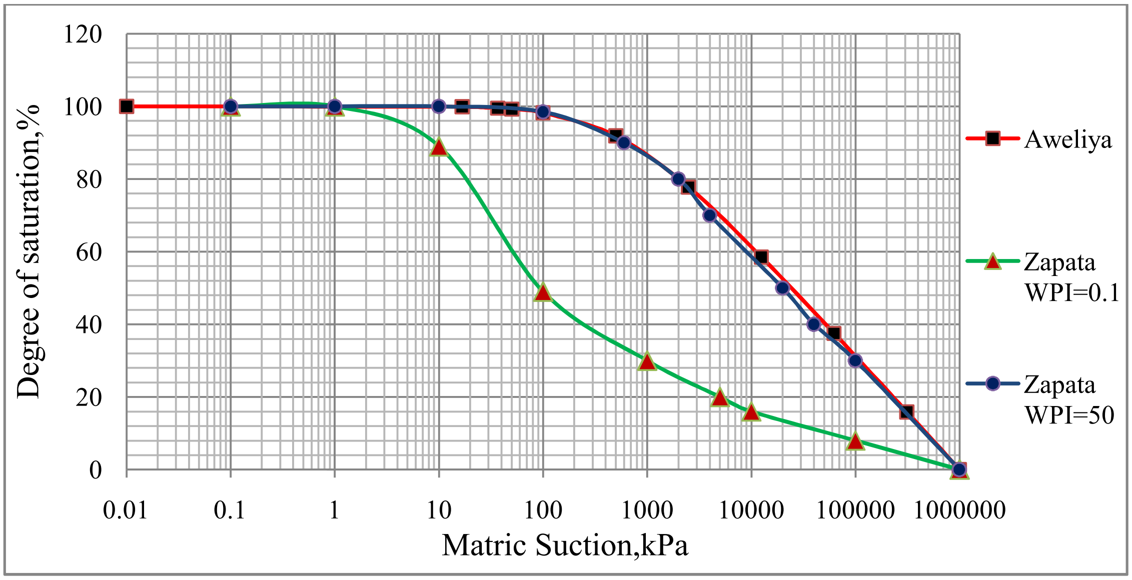



Figure 4. 3 Soil-water characteristic curves for Aweliya site along with Zapata's upper and lower limit for plastic soils

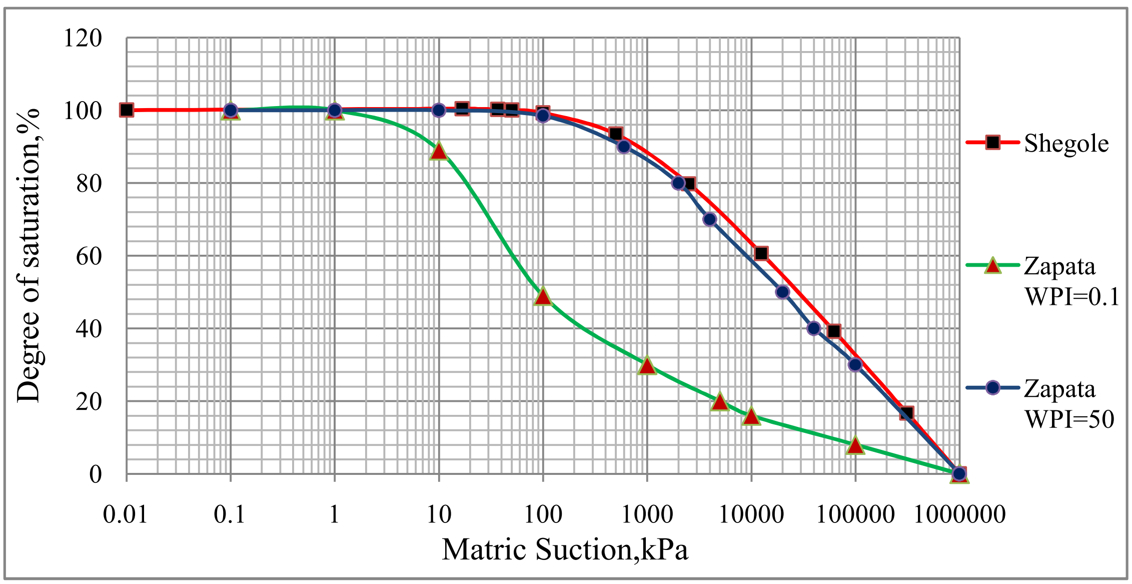



Figure 4. 4 Soil-water characteristic curves for Shegole site along with Zapata's upper and lower limit for plastic soils

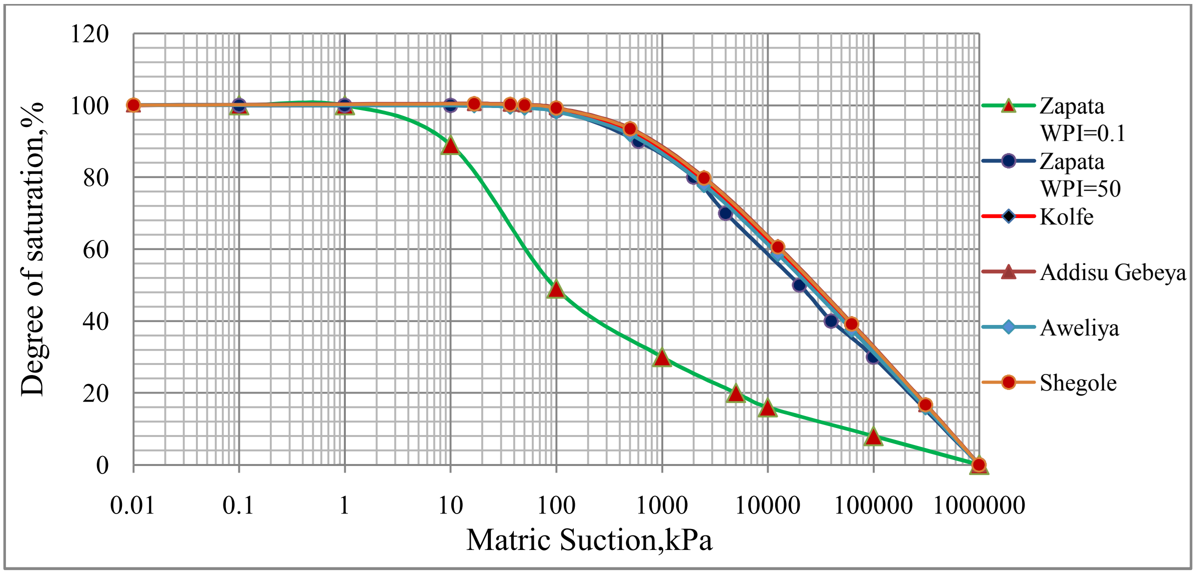



Figure 4. 5 Soil-water characteristic curves for red clay samples along with Zapata's upper and lower limit for plastic soils

The following figures 4.6 to 4.10 present the predicted SWCC for expansive soil samples. As it can be seen from the figures the predicted SWCC curves fall out of the band of Zapata's family of curves similar to that of red clay soil samples.

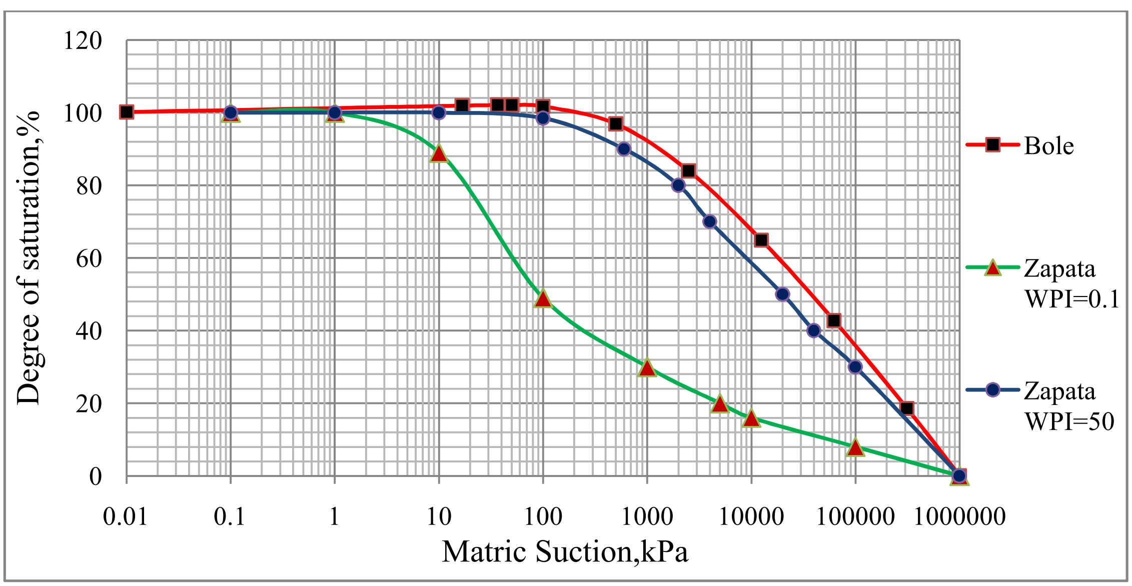



Figure 4. 6 Soil-water characteristic curves for Bole site along with Zapata's upper and lower limit for plastic soils

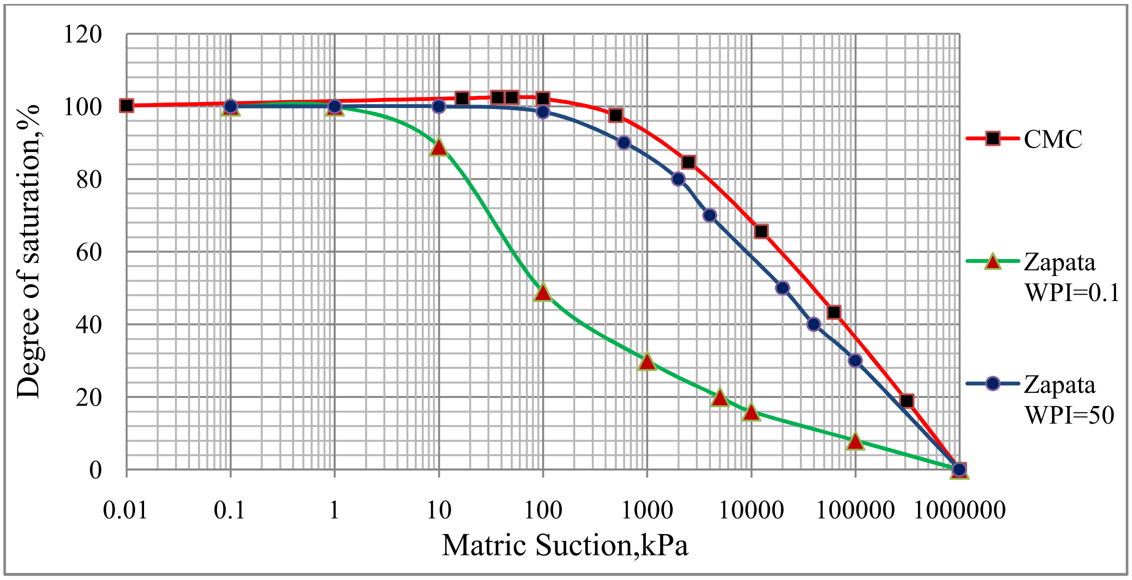



Figure 4. 7 Soil-water characteristic curves for CMC site along with Zapata's upper and lower limit for plastic soils

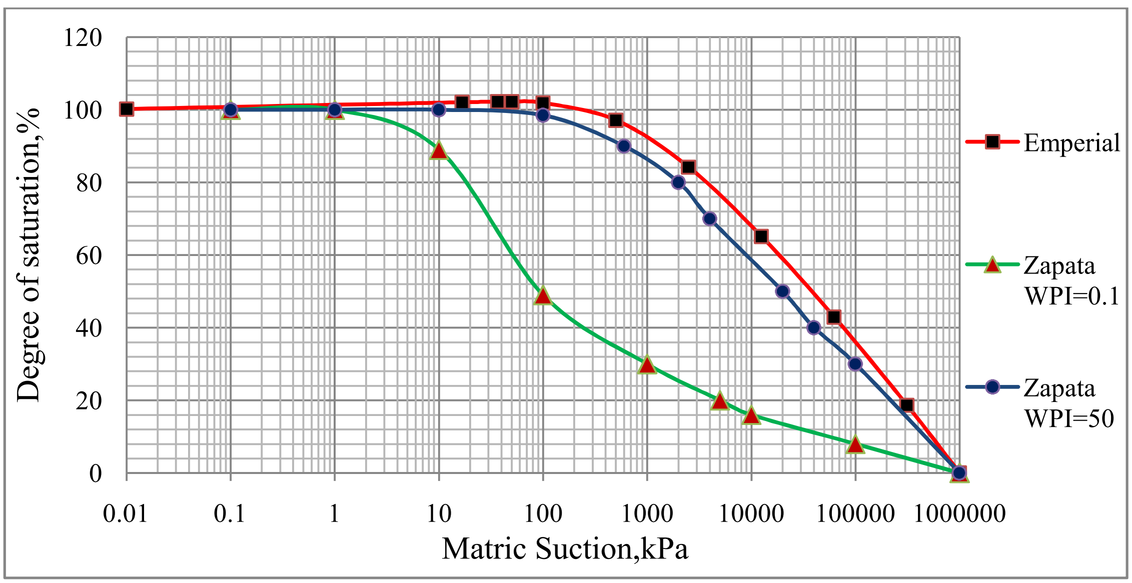



Figure 4. 8 Soil-water characteristic curves for Emperial site along with Zapata's upper and lower limit for plastic soils

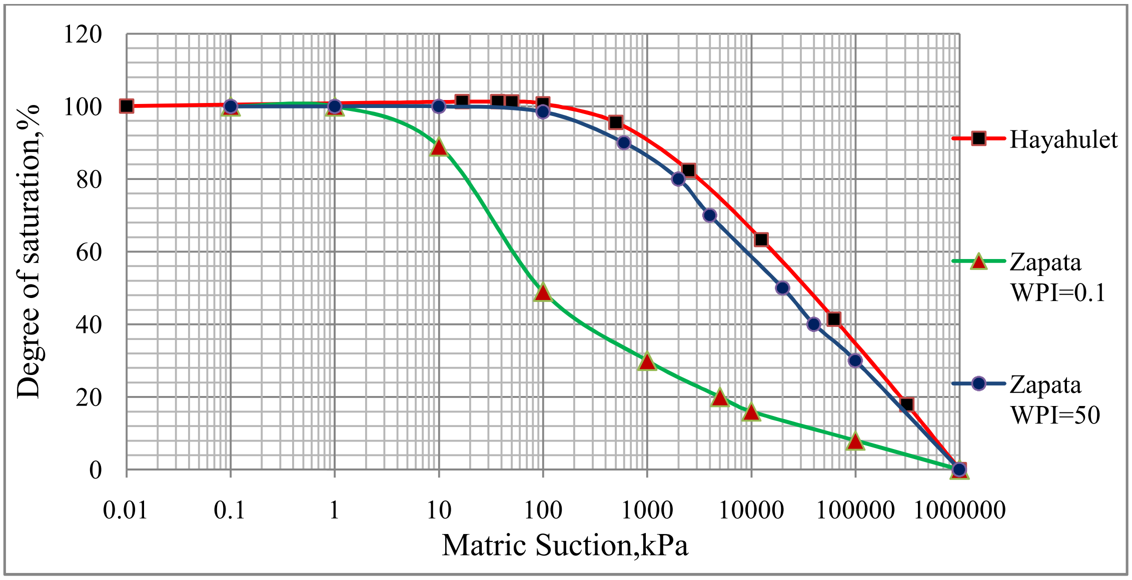



Figure 4. 9 Soil-water characteristic curves for Hayahulet site along with Zapata's upper and lower limit for plastic soils

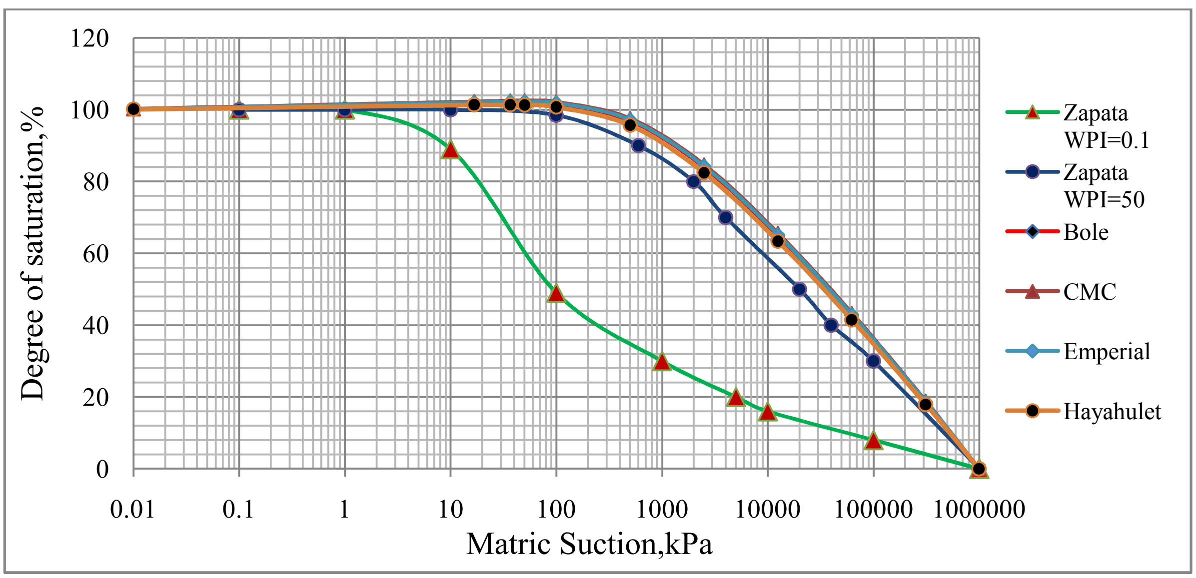



Figure 4. 10 Soil-water characteristic curves for expansive soil samples along with Zapata's upper and lower limit for plastic soils

In this research an attempt was also made to develop family of Soil-water characteristic curve for red clay and expansive soil samples of the study area by using data's from previous researches. Data's for red clay sample from previous research was taken from Samuel, 1989 while for expansive soil samples the necessary data was take from Berhane, 1994. The developed family of soil-water characteristic curve for the study area was plotted in figure 4.11 to 4.13.

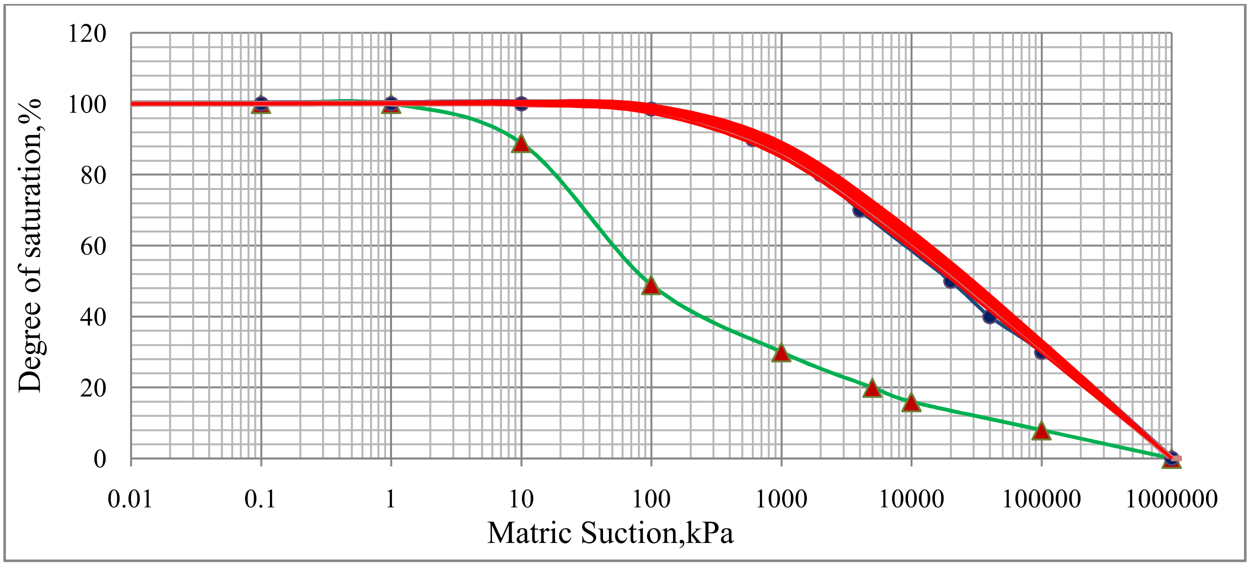



Figure 4. 11 Family of Soil-water characteristic curves (SWCC) for red clay soil samples of Addis Ababa along with Zapata's upper and lower limit for plastic soils

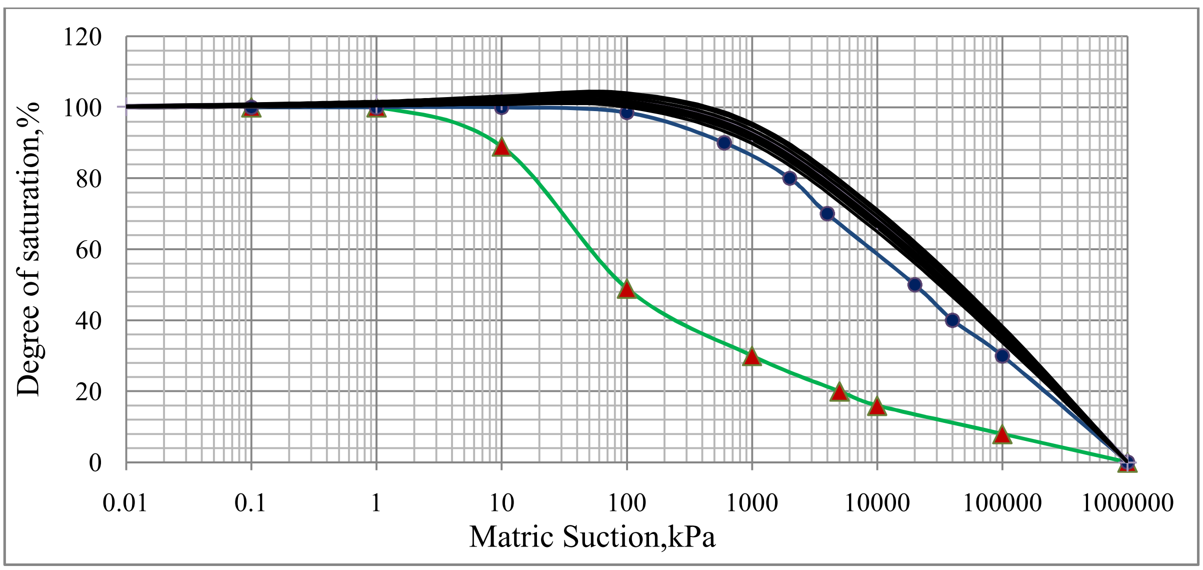



Figure 4. 12 Family of Soil-water characteristic curves (SWCC) for expansive soil samples of Addis Ababa along with Zapata's upper and lower limit for plastic soils

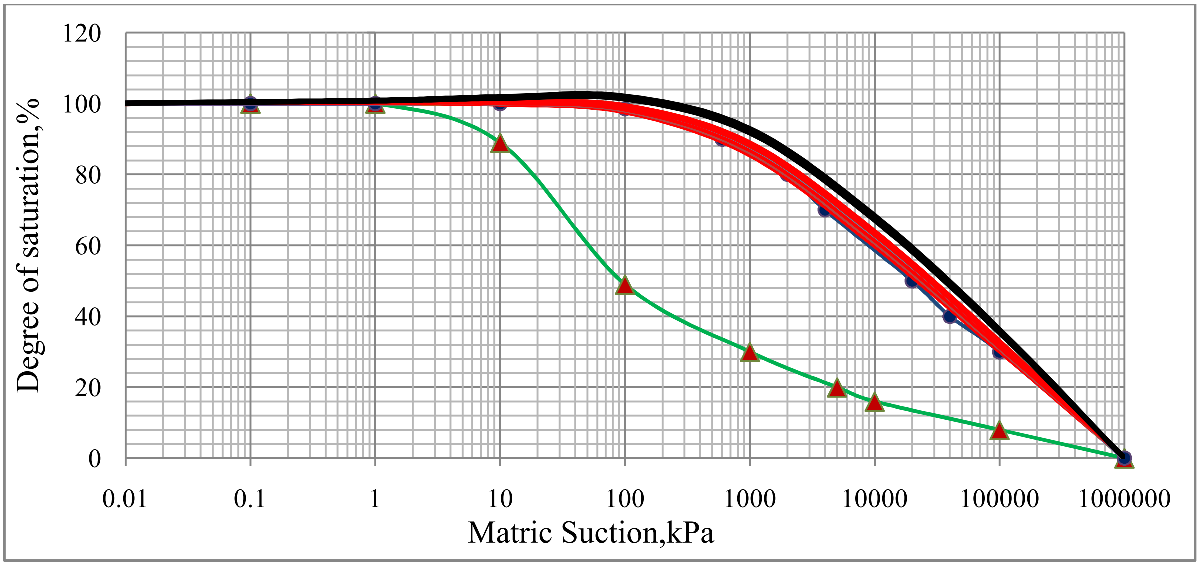



Figure 4. 13 Family of Soil-water characteristic curves (SWCC) for expansive and red clay soil samples of Addis Ababa along with Zapata's upper and lower limit for plastic soils

## 4.2. Prediction of unsaturated shear strength parameter, $\Phi^b$

In order to check the accuracy of the prediction of the model, experimentally measured value of unsaturated shear strength parameter $\Phi^b$ from master's thesis works of Getaneh, 2010 (for red clay soils) and Habtom,2010 (for expansive soils) are compared with the predicted ones. $\Phi^b$ value was predicted using equation (2.14 and 2.15) by using the saturated shear strength parameters along with matric suction at failure obtained from Getaneh, 2010 and Habtom, 2010.

Table 4. 1A $\mathbf{\Phi^b}$ prediction using saturated shear strength parameter from Getaneh, 2010 and the developed SWCC's for red clay samples (Kolfe, Addisu Gebeya and Aweliya sites)

| Matric Suction At failure (kPa) | C' (kPa) | Φ'(°) | $\Phi^b$ Getaneh (°) | SITE | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Kolfe | | Addisu Gebeya | | Aweliya | |
| | | | | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error |
| 16.75 | 36.19 | 21 | 18.8 | 21.12 | 12.34 | 21.21 | 12.82 | 20.95 | 11.42 |
| 36.67 | 36.19 | 21 | 21.55 | 21.00 | 2.54 | 21.13 | 1.97 | 20.77 | 3.63 |
| 50.2 | 36.19 | 21 | 22.22 | 20.90 | 5.92 | 21.04 | 5.30 | 20.64 | 7.11 |
| 21.5 | 20.99 | 25 | 20.1 | 25.11 | 24.93 | 25.22 | 25.49 | 24.89 | 23.84 |
| 42.8 | 20.99 | 25 | 23.6 | 24.95 | 5.73 | 25.10 | 6.37 | 24.67 | 4.53 |
| 52.9 | 20.99 | 25 | 25.87 | 24.87 | 3.88 | 25.03 | 3.25 | 24.56 | 5.07 |

Table 4. 1 B $\Phi^b$ prediction using saturated shear strength parameter from Getaneh, 2010 and the developed SWCC's for red clay samples (Shegole site)

| Matric Suction At failure (kPa) | C' (kPa) | $\Phi'(^o)$ | $\Phi^b$ Getaneh ($^o$) | SITE | |
|---|---|---|---|---|---|
| | | | | Shegole | |
| | | | | $\Phi^b$ Predicted | % Error |
| 16.75 | 36.19 | 21 | 18.8 | 21.19 | 12.73 |
| 36.67 | 36.19 | 21 | 21.55 | 21.10 | 2.07 |
| 50.2 | 36.19 | 21 | 22.22 | 21.02 | 5.41 |
| 21.5 | 20.99 | 25 | 20.1 | 25.20 | 25.39 |
| 42.8 | 20.99 | 25 | 23.6 | 25.08 | 6.25 |
| 52.9 | 20.99 | 25 | 25.87 | 25.00 | 3.36 |

Table 4. 2 A $\Phi^b$ prediction using saturated shear strength parameter from Habtom, 2010 and the developed SWCC's for expansive soil samples (Bole and CMC sites)

| Matric Suction At failure (kPa) | C' (kPa) | $\Phi'(^o)$ | $\Phi^b$ Habtom ($^o$) | SITE | | | |
|---|---|---|---|---|---|---|---|
| | | | | Bole | | CMC | |
| | | | | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error |
| 23.1 | 7.32 | 12.74 | 12.26 | 12.96 | 5.70 | 12.73 | 3.86 |
| 32.9 | 7.32 | 12.74 | 13.56 | 12.96 | 4.41 | 12.73 | 6.13 |
| 48.6 | 7.32 | 12.74 | 10.70 | 12.96 | 21.12 | 12.73 | 18.94 |
| 14.5 | 5.39 | 13.96 | 12.75 | 14.18 | 11.23 | 13.95 | 9.45 |
| 38.8 | 5.39 | 13.96 | 10.17 | 14.20 | 39.64 | 13.95 | 37.13 |
| 52 | 5.39 | 13.96 | 12.53 | 14.20 | 13.35 | 13.95 | 11.33 |

Table 4. 2 B $\Phi^b$ prediction using saturated shear strength parameter from Habtom, 2010 and the developed SWCC's for expansive soil samples (Emperial and Hayahulet Sites)

| Matric Suction At failure (kPa) | C' (kPa) | $\Phi'(^o)$ | $\Phi^b$ Habtom ($^o$) | SITE | | | |
|---|---|---|---|---|---|---|---|
| | | | | EMPERIAL | | HAYAHULET-22 | |
| | | | | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error |
| 23.1 | 7.32 | 12.74 | 12.26 | 12.86 | 4.94 | 12.99 | 5.94 |
| 32.9 | 7.32 | 12.74 | 13.56 | 12.87 | 5.11 | 12.99 | 4.24 |
| 48.6 | 7.32 | 12.74 | 10.70 | 12.87 | 20.23 | 12.97 | 21.20 |
| 14.5 | 5.39 | 13.96 | 12.75 | 14.08 | 10.49 | 14.21 | 11.50 |
| 38.8 | 5.39 | 13.96 | 10.17 | 14.10 | 38.61 | 14.22 | 39.84 |
| 52 | 5.39 | 13.96 | 12.53 | 14.10 | 12.53 | 14.21 | 13.40 |

In addition to soil samples from Addis Ababa, soil-water characteristic curve of expansive soil samples of Arbaminch and silty soils of Hawasa were predicted using data's of Bantayehu, 2011 and Eyob, 2011 respectively. Figure 4.14 shows the predicted SWCC for expansive soil of Arbaminch which lies above the upper limit of Zapata's family of curves for plastic soil similar to those samples of Addis Ababa. As it can be seen from Table 4.3 the percentage error between measured and predicted unsaturated shear strength parameter $\Phi^b$ lies in the range 31-61% for all samples. From this result it can be concluded that the predicted SWCC gives poor result as compared to results obtained for Addis Ababa soil samples.

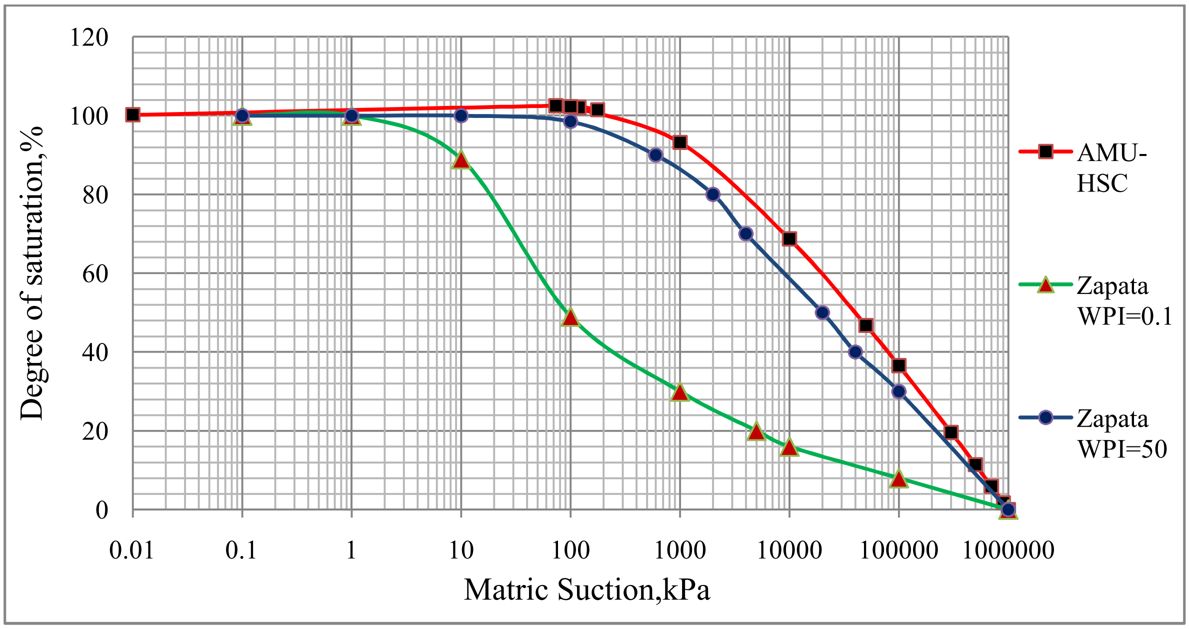



Figure 4. 14 Predicted SWCC for expansive soil from Arbaminch with Zapata's SWCC

Table 4. 3 Comparison of measured and predicted Φb for expansive soils from Arbaminch using data's of Bantayehu, 2011

| Matric Suction At failure | C' | Φ' | $\Phi^b$ Bantayehu, 2011 | SITE | |
|---|---|---|---|---|---|
| | | | | AMU-HSC | |
| | | | | $\Phi^b$ Predicted | % Error |
| 73..34 | 25.6 | 11.7 | 8.8 | 11.55 | 31.21 |
| 119.28 | 25.6 | 11.7 | 8.6 | 11.57 | 34.54 |
| 176.46 | 25.6 | 11.7 | 7.2 | 11.61 | 61.24 |

It is also attempted to predict the soil-water characteristic curve for silty soils of Hawasa based on the results of Eyob, 2011. Figure 4.15 below shows the predicted SWCC for the sample using correlation equation developed by Perera *et.al 2005* for non-Plastic soil samples.

Among the soil samples taken by Eyob, 2011 three of them show non-plastic behavior while one sample shows plastic behavior. SWCC is predicted using both groups of sample.

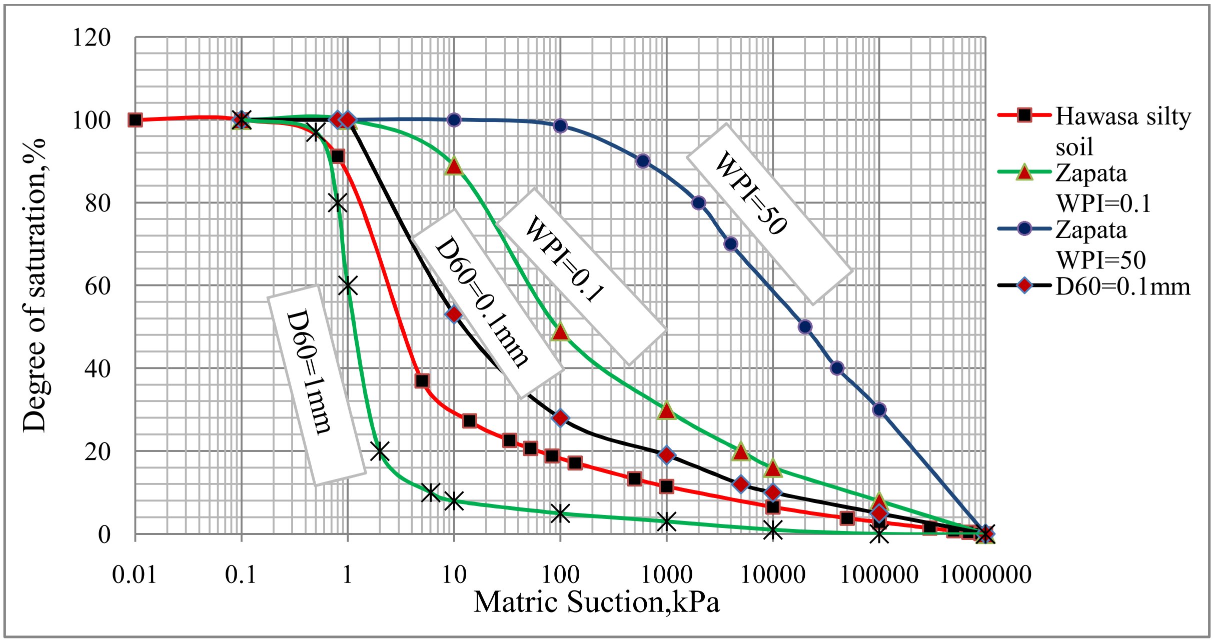



Figure 4. 15 Predicted SWCC for silty soil of Hawasa using non-plastic soil sample data along with Zapata's family of SWCC.

The predicted SWCC using non –plastic soil sample falls within the range of Zapata’s family of curve as it can be seen from the above plot. However, the unsaturated shear strength parameter $\Phi^b$ values predicted using this SWCC do not have close agreement with measured values. The predicted SWCC gives poor result regarding the prediction of unsaturated shear strength parameter $\Phi^b$ .The percentage error between the measured and predicted $\Phi^b$ lies in the range of 68-89%.

Table 4. 4 Comparison of measured and predicted Φb for silty soils from Hawasa using data’s of Eyob, 2011 using $\kappa = 1.0$

| $\kappa$=1 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Matric Suction At failure | C' | Φ' | $\Phi^b$ Eyob | (Eyob, 2011 ) | | | | | |
| | | | | Pit#1 | | Pit#3 | | Pit#4 | |
| | | | | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error |
| 13.9 | 8.33 | 26.95 | 26.93 | 4.21 | 84.38 | 5.29 | 80.36 | 5.89 | 78.14 |
| 33.09 | 8.33 | 26.95 | 25.81 | 3.36 | 86.98 | 4.35 | 83.16 | 4.83 | 81.27 |
| 52.4 | 8.33 | 26.95 | 24.57 | 3.02 | 87.69 | 3.96 | 83.88 | 4.40 | 82.07 |
| 83.56 | 8.33 | 26.95 | 24.31 | 2.73 | 88.77 | 3.62 | 85.13 | 4.02 | 83.47 |
| 137.45 | 8.33 | 26.95 | 11.64 | 2.45 | 78.95 | 3.28 | 71.82 | 3.64 | 68.70 |

The prediction seems to be improved if the value of $\kappa$ is set to be equal to 0.05. In this case the predicted SWCC gives good result in prediction of $\Phi^b$. The percentage error between the measured and predicted $\Phi^b$ value is found to lie in the range 0.01-8.0% except for high suction value of 137.45kPa in which the error is in the range 107-112%.

Table 4. 5 Comparison of measured and predicted Φb for silty soils from Hawasa using data's of Eyob, 2011 using k=0.05

| $\kappa$=0.05 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Matric Suction At failure | C' | Φ' | $\Phi^b$ Eyob | (Eyob, 2011) | | | | | |
| | | | | Pit#1 | | Pit#3 | | Pit#4 | |
| | | | | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error | $\Phi^b$ Predicted | % Error |
| 13.9 | 8.33 | 26.95 | 26.93 | 24.78 | 8.00 | 25.03 | 7.06 | 25.15 | 6.62 |
| 33.09 | 8.33 | 26.95 | 25.81 | 24.53 | 4.95 | 24.81 | 3.86 | 24.93 | 3.41 |
| 52.4 | 8.33 | 26.95 | 24.57 | 24.42 | 0.62 | 24.71 | 0.58 | 24.83 | 1.05 |
| 83.56 | 8.33 | 26.95 | 24.310 | 24.308 | 0.009 | 24.61 | 1.24 | 24.73 | 1.71 |
| 137.45 | 8.33 | 26.95 | 11.64 | 24.19 | 107.83 | 24.51 | 110.53 | 24.62 | 111.51 |

Soil-water characteristic curve for the Hawasa soil sample with PI > 0 is also predicted using data obtained from the model. The predicted SWCC lies between the two upper and lower limits of Zapata's family of curves for plastic soil sample as shown in the figure below. The predicted $\Phi^b$ value for this case is good as compared to those values obtained using the non-plastic soil sample data. The percentage error is improved to be in the range 4.0-8.0%. For higher suction value of 137.45 kPa, the error is about 78%.

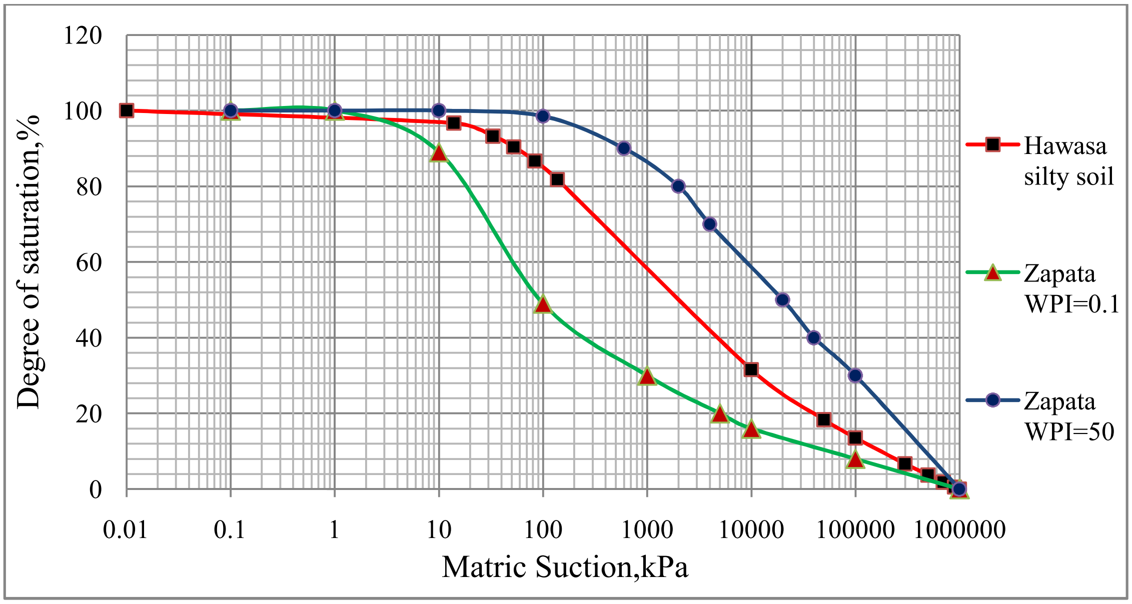



Figure 4. 16 Predicted SWCC for Hawasa silty soil using plastic soil sample from test pit#2 of Eyob, 2011

Table 4. 6 Comparison of measured and predicted Φb for silty soils from Hawasa using data's of plastic soil sample of Eyob, 2011

| Plastic soil sample of Hawasa | | | | | |
|---|---|---|---|---|---|
| Matric Suction At failure | C' | Φ' | $\Phi^b$ ,Eyob | (Eyob,2011) Pit#2 | |
| | | | | $\Phi^b$ Predicted | % Error |
| 13.9 | 8.33 | 26.95 | 26.93 | 25.84 | 4.04 |
| 33.09 | 8.33 | 26.95 | 25.81 | 24.68 | 4.40 |
| 52.4 | 8.33 | 26.95 | 24.57 | 23.71 | 3.48 |
| 83.56 | 8.33 | 26.95 | 24.31 | 22.45 | 7.63 |
| 137.45 | 8.33 | 26.95 | 11.64 | 20.80 | 78.70 |

As it can be seen from Table 4.4 the obtained result for non-plastic soil samples of Hawasa was not in close agreement with the measured values as compared to result obtained for plastic soil samples summarized in Table 4.6. It was assumed that the error might arise from the fitting parameter $\kappa$, which is a fitting parameter used to account for non-linearity between area and volume representation of the amount of water contributing to the shear strength. $\kappa$ was computed using equation (2.16) in section 2.4.4 which is correlation equation developed using plasticity index by Garven and Vanapalli (2006).

For non plastic soil samples, $\kappa$=1 based on this equation. It was observed that the predicted $\Phi^b$ value is sensitive to change in $\kappa$ value. The result seems to be improved as $\kappa$ value decreases. $\kappa$ =0.05 gave good result which improved the percentage error from 68.0%-84.0% to the range 0.01-8.0% except for high suction value of 137.5kPa in which the percentage error increased from 78.95% to 111.5% .

The plot of contribution of matric suction to shear strength using measured and predicted values of $\Phi^b$ for red clay samples from Kolfe and for expansive soils from Bole, CMC and Arbaminch are shown below in figure 4.17and 4.18 respectively.

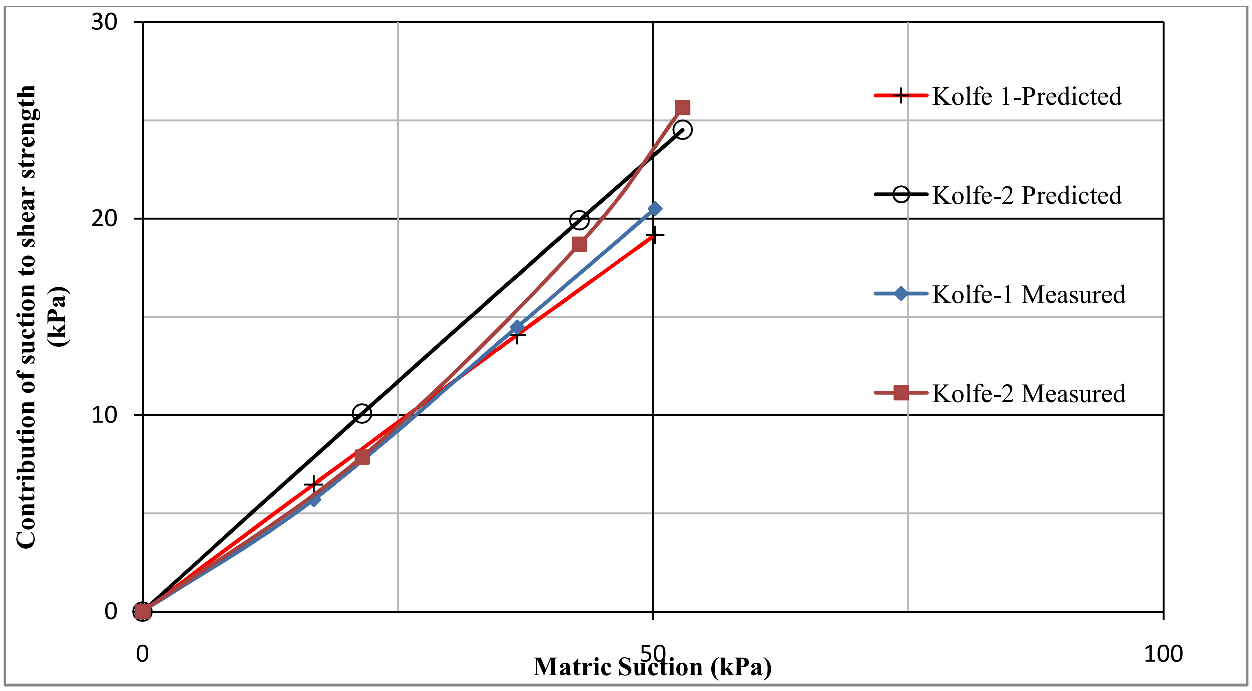



Figure 4. 17 Contribution of suction to shear strength for Kolfe-Getaneh-2010 using measured and predicted $\Phi^b$ value.

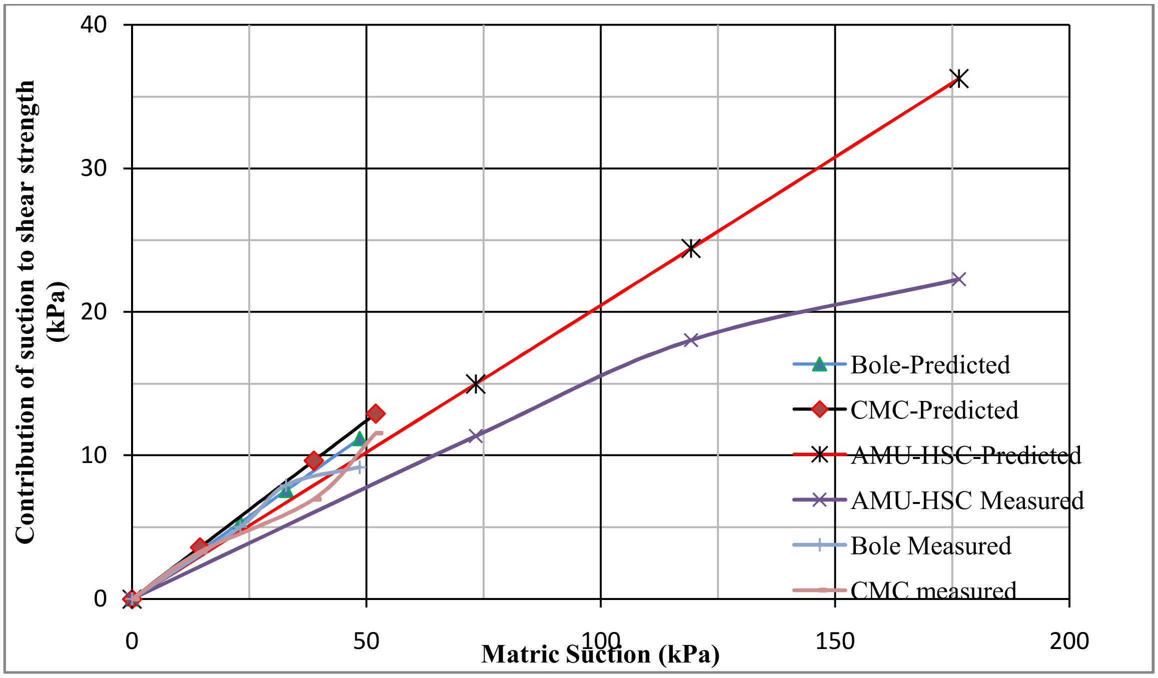



Figure 4. 18 Contribution of suction to shear strength for Bole, CMC and Arbaminch area soils using measured and predicted $\Phi^b$ value.

From the above two plots one can see that the increase of contribution of suction to shear strength shows linear increase for the predicted values while it shows non-linear increase for the measured values. For soil samples from Bole and CMC the predicted and measured values of the contribution of suction to shear strength were close to each other while it is a bit far from each other for Arbaminch soils.

# CHAPTER 5

## 5. CONCLUSION AND RECOMMENDATION

### 5.1. Conclusion

From the test results that are summarized in Tables and figures presented in Chapter 4, the following conclusions can be drawn:

1. The predicted soil-water characteristic curve for both red clay and expansive soil samples fall out of the band given by Zapata, 2000, which is the only model used for comparison in this paper. Comparing the predicted SWCC for both red clay and expansive soil samples, the predicted SWCC for expansive soil samples fall far from Zapata's upper limit while those of red clay samples fall close to the upper limit. These results indicate that the predictive model may not work well for our soils. The mineralogical composition of the soils in Addis Ababa and those soils used in developing Zapata's family of curve might be different.

2. The predicted unsaturated shear strength parameter $\Phi^b$ for red clay samples shows proximity to the measured values. The percentage error ranges from 2.07 to 6.37% for suction ranges of 36.67 to 52.9 kPa and at initial suction of 16.75 and 21.5 kPa the percentage error ranges from 11.42 to 25.39%. From this value the model seems to be less precise at lower suctions and better at higher suctions.

3. The percentage error of the predicted unsaturated shear strength parameter $\Phi^{\mathbf{b}}$ from the measured values for expansive soil samples for suction of 23.1 and 32.9 kPa, range from 3.86 to 6.13%. For suction values of 14.5 and 52 kPa the range of error is about 9.45 to 13.40% and for suction values of 38.8 and 48.6 kPa the error lies between 18.94 and 38.84%.

4. As it can be observed from the above summarized facts the prediction of the model is found to be satisfactory at certain suction ranges considering the fact that the error may also arise from the measured values obtained from unsaturated tri-axial machine by Getaneh, 2010 and Habtom, 2010 for red clay and expansive soil samples respectively.

5. In addition to red clay and expansive soil samples of Addis Ababa, as stated in section 4.3 SWCC for expansive soils of Arbaminch area and Silty soils of Hawasa was also predicted. From the analysis it was observed that the predicted SWCC gave poor result for Expansive soil samples of Arbaminch as compared to expansive soils of Addis Ababa. The percentage error of the predicted $\Phi^b$ value found to lie in the range 31.0%-62.0%.

6. Similar to Arbaminch area expansive soil samples, the data obtained from the predicted SWCC of silty soils of Hawasa town is not satisfactory. Predicted SWCC using plastic soil samples gave good result as compared to those results obtained using non-plastic samples data. The percentage error for non-plastic soil samples lie in the range 68.0%-84.0% while it falls in the range 3.0%-7.63% for plastic soil sample from pit#2 except at suction value of 137.45kPa in which the error is exaggerated to about 78.7%.

7. In the case of Hawasa soils, it was also observed that the predicted $\Phi^b$ value is sensitive to change in fitting parameter $\kappa$ for non-plastic soil samples. For non plastic soil from Hawasa the result is improved by changing $\kappa = 1$ to $\kappa = 0.05$. The percentage error is improved from 68.0%-84.0% to the range 0.01-8.0% except for high suction value of 137.5kPa in which the percentage error increased from 78.95% to 111.5%.

## 5.2. Recommendation

Even if the predicted family of curves for red clay and expansive soil samples taken from Addis Ababa fall out of the band of Zapata's family of curves, the predicted SWCC give satisfactory result in prediction of the unsaturated shear strength parameter $\Phi^b$. So the model can be used for prediction of unsaturated shear strength for the soils in the study area without carrying out unsaturated shear strength test which is expensive and time consuming. It uses only c' and Φ' values from saturated tri-axial test, $P_{200}$ from grain size distribution test and PI from Atterberg limit test.

More unsaturated shear strength tests on a wide range of suction and saturated shear strength tests along with grain size distribution and index properties have to be conducted to check the validity of the results.

It is recommended that further investigations of unsaturated shear strength of both plastic and non-plastic soils be carried out and compared with the prediction of the model in order to identify the cause for inaccuracy of the prediction.

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# APPENDIX

Table A- 1 Data sheet of liquid limit and plastic limit for Kolfe site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | 26 | D361 | C35 | 1A | H4 | 107 |
| Weight of can, Wc (g) | 14.15 | 15.75 | 13.94 | 15.32 | 15.77 | 15.84 |
| Weight of can with wet soil, Ww (g) | 20.33 | 23.52 | 21.02 | 22.19 | 21.42 | 23.83 |
| Weight of can with dry soil, Wd (g) | 17.68 | 20.42 | 17.91 | 19.29 | 20.05 | 21.99 |
| Number of Blow count, N | 22 | 37 | 15 | 28 | ------ | ------ |
| Water content, W(%) | 75.11 | 66.26 | 78.03 | 73.18 | 32.21 | 30.06 |
| Liquid Limit, % | 73.43 | PI, % | 42.29 | PL, average,% | | 31.13 |

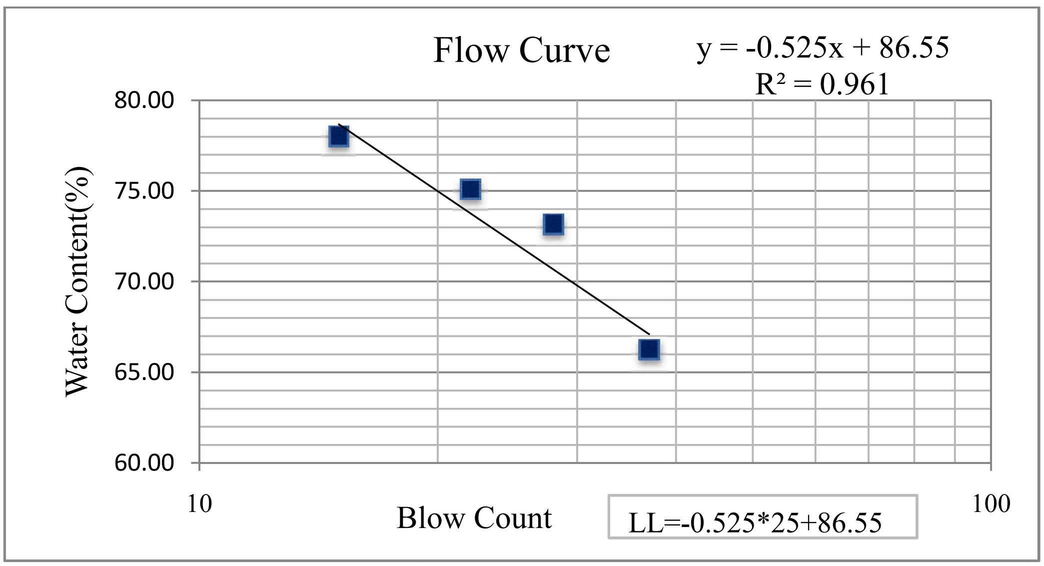


Figure A- 1 Flow curve of Kolfe site sample at 1.5m depth

Table A- 2 Data sheet of liquid limit and plastic limit for Kolfe site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | A-10 | 98 | 53 | 21 | A16 | 9 |
| Weight of can, Wc (g) | 15.56 | 15.59 | 15.56 | 15.56 | 15.78 | 15.70 |
| Weight of can with wet soil, Ww (g) | 21.57 | 24.06 | 23.80 | 21.93 | 21.26 | 21.22 |
| Weight of can with dry soil, Wd (g) | 19.25 | 20.58 | 20.49 | 19.45 | 19.99 | 19.97 |
| Number of Blow count, N | 36 | 14 | 24 | 29 | ------ | ------ |
| Water content, W (%) | 63.21 | 69.59 | 67.11 | 63.94 | 30.15 | 29.21 |
| Liquid Limit, % | 66.21 | PI, % | 36.52 | PL, average,% | | 29.68 |

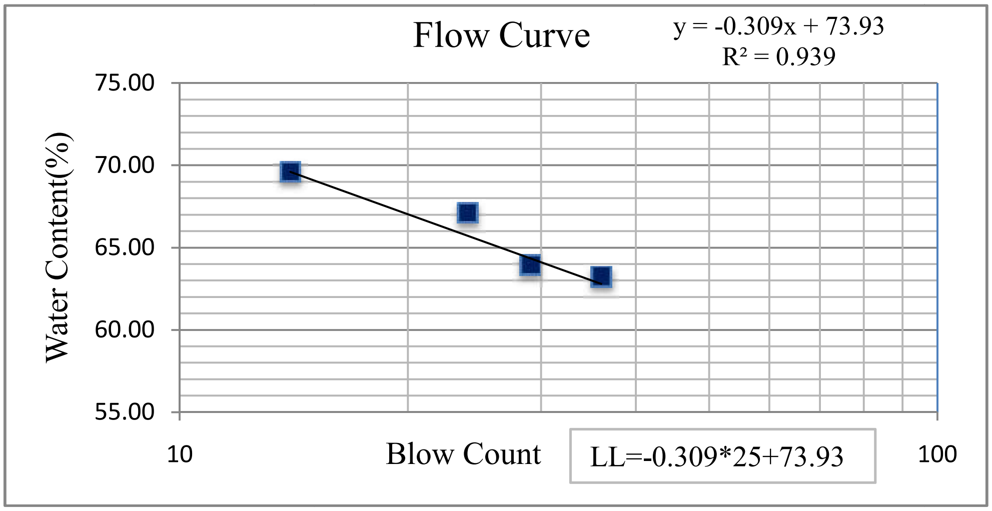


Figure A- 2 Flow curve of Kolfe site sample at 2.5m depth

Table A- 3 Data sheet of liquid limit and plastic limit for Addisu Gebeya site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | D-5 | D-21 | 107 | A-29 | C-16 | C-8 |
| Weight of can, Wc (g) | 15.70 | 15.63 | 15.82 | 15.34 | 14.20 | 13.71 |
| Weight of can with wet soil, Ww (g) | 23.07 | 23.30 | 22.88 | 22.74 | 18.57 | 18.31 |
| Weight of can with dry soil, Wd (g) | 20.14 | 20.04 | 19.98 | 19.53 | 17.58 | 17.25 |
| Number of Blow count, N | 37 | 22 | 31 | 14 | ------ | ------ |
| Water content, W (%) | 65.90 | 73.78 | 69.57 | 76.61 | 29.20 | 30.03 |
| Liquid Limit, % | 71.95 | PI, % | 42.34 | PL, average,% | | 29.61 |

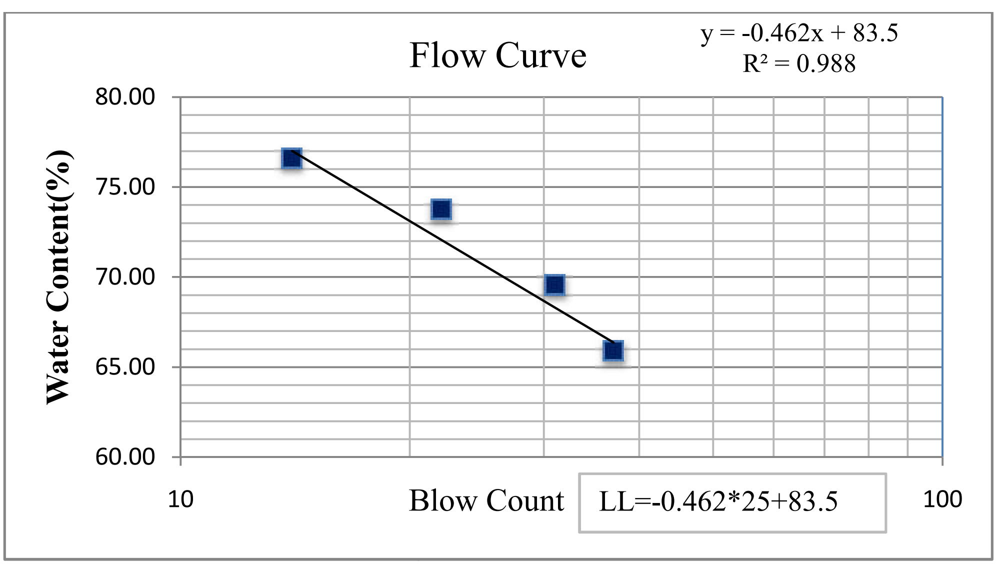


Figure A- 3 Flow curve of Addisu Gebeya site sample at 1.5m depth

Table A- 4 Data sheet of liquid limit and plastic limit for Addisu Gebeya site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | 98 | C-29 | 35 | 47 | A-1 | 26 |
| Weight of can, Wc (g) | 15.57 | 14.05 | 15.63 | 15.69 | 11.50 | 14.16 |
| Weight of can with wet soil, Ww (g) | 26.32 | 22.55 | 25.41 | 22.95 | 15.23 | 17.89 |
| Weight of can with dry soil, Wd (g) | 21.85 | 19.00 | 21.28 | 19.86 | 14.32 | 16.96 |
| Number of Blow count, N | 38 | 30 | 21 | 18 | ------ | ------ |
| Water content, W(%) | 71.01 | 71.54 | 73.10 | 74.24 | 32.64 | 33.18 |
| Liquid Limit, % | 72.75 | PI, % | 39.84 | PL, average,% | | 32.91 |

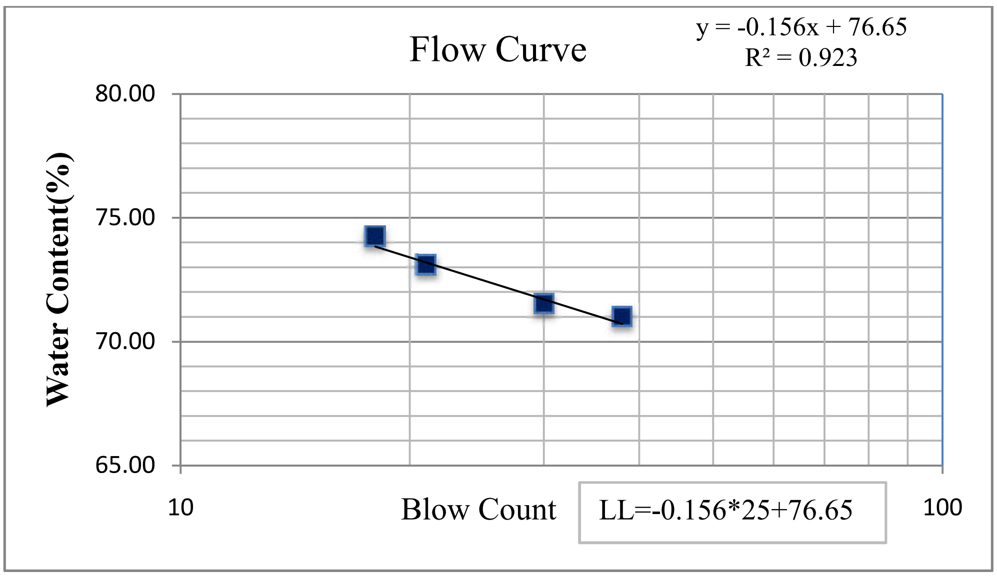


Figure A- 4 Flow curve of Addisu Gebeya site sample at 2.5m depth

Table A- 5 Data sheet of liquid limit and plastic limit for Aweliya site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | 45 | 79 | GHI | 59 | 10* | D-23 |
| Weight of can, Wc (g) | 15.44 | 15.51 | 15.60 | 15.33 | 15.68 | 15.38 |
| Weight of can with wet soil, Ww (g) | 22.82 | 21.86 | 21.83 | 21.37 | 18.53 | 18.86 |
| Weight of can with dry soil, Wd (g) | 19.82 | 19.38 | 19.50 | 19.08 | 17.86 | 18.05 |
| Number of Blow count, N | 15.00 | 23.00 | 36.00 | 29.00 | ------ | ------ |
| Water content, W(%) | 68.52 | 64.28 | 59.70 | 60.83 | 30.88 | 30.52 |
| Liquid Limit, % | 63.67 | PI, % | 32.97 | PL, average,% | | 30.70 |

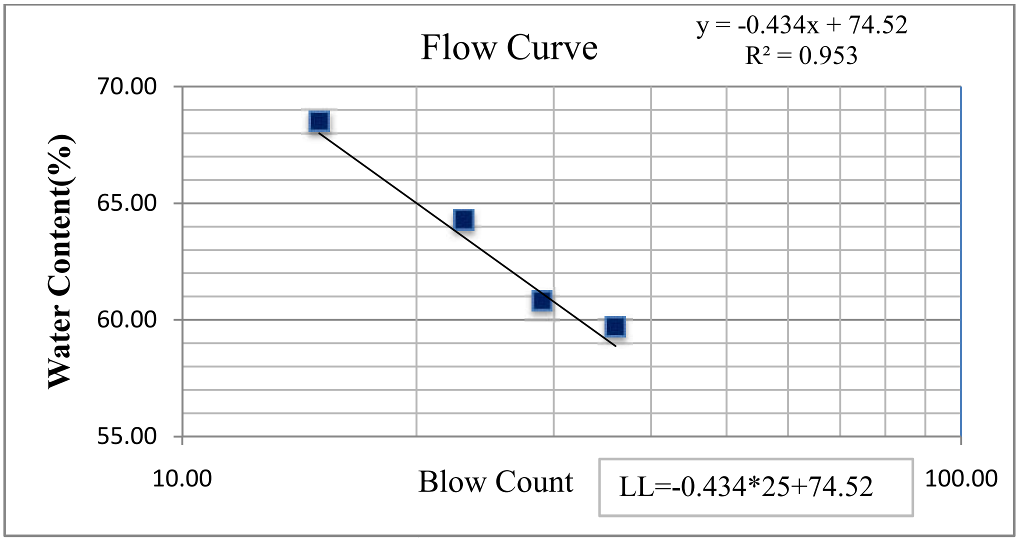


Figure A- 5 Flow curve of Aweliya site sample at 1.5m depth

Table A- 6 Data sheet of liquid limit and plastic limit for Aweliya site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | D-25 | C-31 | 35 | 40 | A-25 | D-5 |
| Weight of can, Wc (g) | 15.87 | 14.05 | 15.62 | 15.32 | 15.78 | 15.70 |
| Weight of can with wet soil, Ww (g) | 22.53 | 21.86 | 23.61 | 22.39 | 19.11 | 19.89 |
| Weight of can with dry soil, Wd (g) | 19.99 | 18.81 | 20.44 | 19.62 | 18.31 | 18.92 |
| Number of Blow count, N | 38 | 30 | 19 | 24 | ------ | ------ |
| Water content, W (%) | 61.55 | 63.79 | 65.62 | 64.29 | 31.40 | 30.11 |
| Liquid Limit, % | 64.38 | PI, % | 33.62 | PL, average,% | | 30.75 |

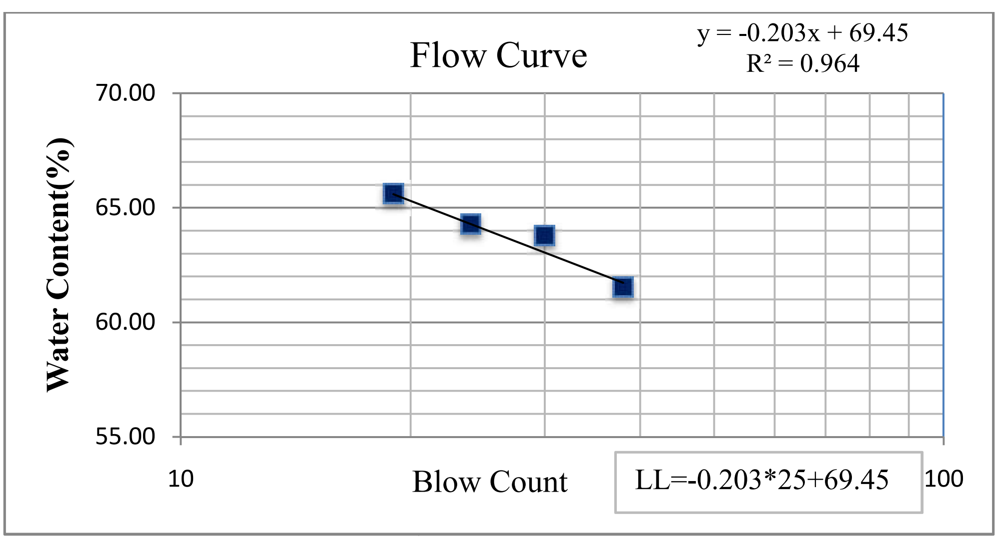


Figure A- 6 Flow curve of Aweliya site sample at 2.5m depth

Table A- 7 Data sheet of liquid limit and plastic limit for Shegole site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | D31 | 100 | 45 | 40 | A16 | H3 |
| Weight of can, Wc (g) | 15.46 | 15.45 | 15.46 | 15.33 | 14.54 | 15.09 |
| Weight of can with wet soil, Ww (g) | 27.80 | 26.73 | 29.05 | 25.78 | 17.19 | 17.52 |
| Weight of can with dry soil, Wd (g) | 22.60 | 22.11 | 23.85 | 21.79 | 16.58 | 16.93 |
| Number of Blow count, N | 16 | 21 | 29 | 38 | ------ | ------ |
| Water content, W(%) | 72.78 | 69.26 | 62.01 | 61.74 | 29.74 | 31.86 |
| Liquid Limit, % | 66.99 | PI, % | 36.18 | PL, average,% | | 30.80 |

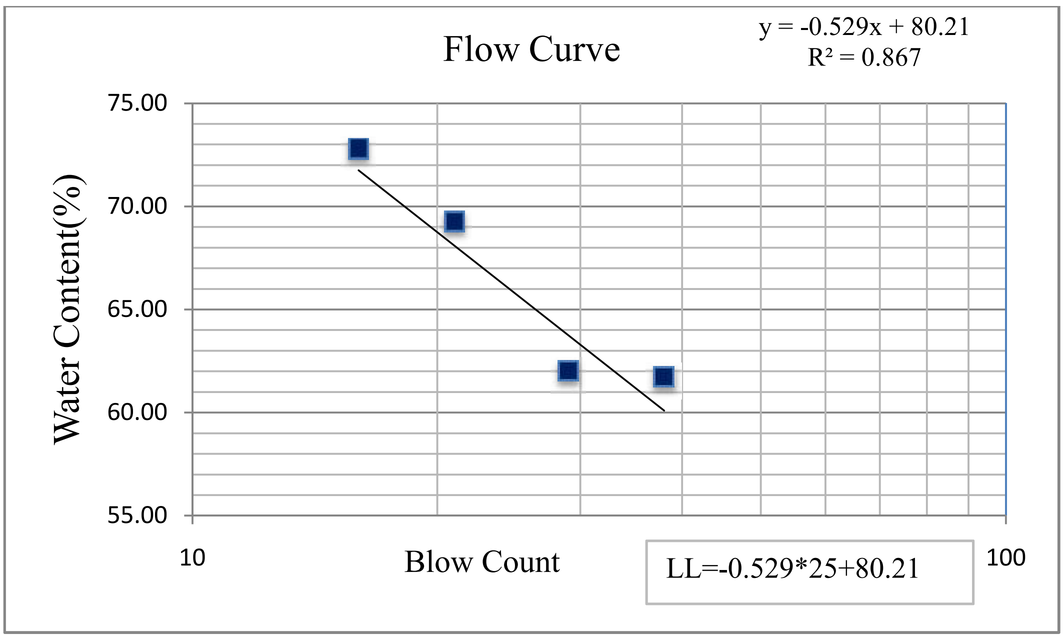


Figure A- 7 Flow curve of Shegole site sample at 1.5m depth

Table A- 8 Data sheet of liquid limit and plastic limit for Shegole site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | 1A | C31 | D4 | 107 | A1 | 31 |
| Weight of can, Wc (g) | 15.29 | 14.08 | 15.95 | 15.84 | 15.59 | 15.44 |
| Weight of can with wet soil, Ww (g) | 28.82 | 28.24 | 30.13 | 29.18 | 17.62 | 17.63 |
| Weight of can with dry soil, Wd (g) | 23.34 | 22.33 | 24.27 | 23.63 | 17.15 | 17.09 |
| Number of Blow count, N | 35 | 18 | 29 | 24 | ------ | ------ |
| Water content, W (%) | 68.11 | 71.69 | 70.44 | 71.11 | 29.86 | 32.34 |
| Liquid Limit, % | 70.66 | PI, % | 39.56 | PL, average,% | | 31.10 |

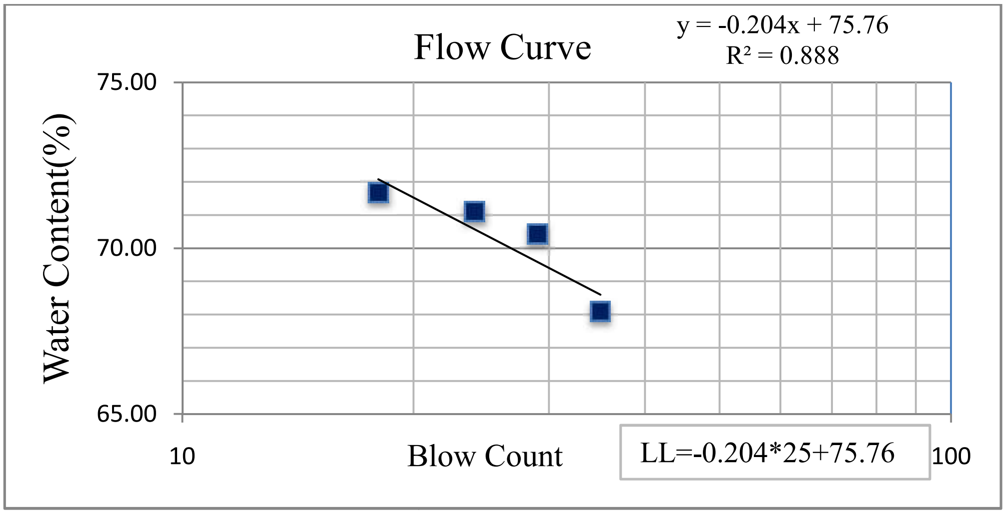


Figure A- 8 Flow curve of Shegole site sample at 2.5m depth

Table A- 9 Data sheet of liquid limit and plastic limit for Bole site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | D-25 | D22 | 15 | C-8 | 47 | H3 |
| Weight of can, Wc (g) | 15.88 | 15.76 | 15.50 | 13.70 | 15.68 | 14.06 |
| Weight of can with wet soil, Ww (g) | 23.11 | 25.40 | 25.13 | 26.22 | 16.94 | 15.67 |
| Weight of can with dry soil, Wd (g) | 19.56 | 20.59 | 20.35 | 19.91 | 16.59 | 15.23 |
| Number of Blow count, N | 37 | 20 | 27 | 12 | ------ | ------ |
| Water content, W (%) | 96.34 | 99.52 | 98.40 | 101.37 | 38.28 | 37.51 |
| Liquid Limit, % | 98.68 | PI, % | 60.78 | PL, average,% | | 37.90 |

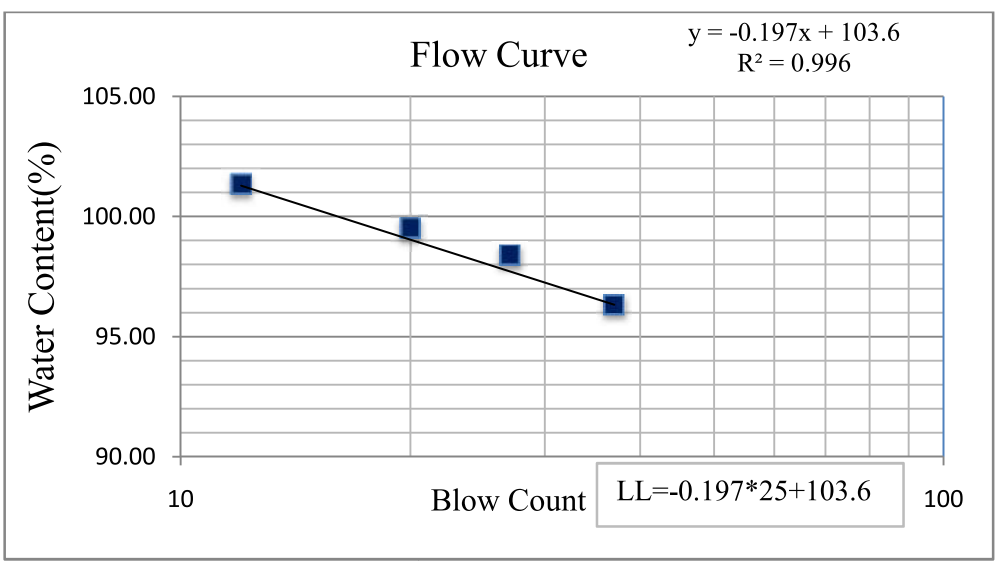


Figure A- 9 Flow curve of Bole site sample at 1.5m depth

Table A- 10 Data sheet of liquid limit and plastic limit for Bole site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | D4 | D-31 | H2 | 69 | D-15 | 85 |
| Weight of can, Wc (g) | 15.96 | 15.46 | 15.70 | 15.74 | 15.62 | 15.84 |
| Weight of can with wet soil, Ww (g) | 24.30 | 25.58 | 25.23 | 25.89 | 17.81 | 17.64 |
| Weight of can with dry soil, Wd (g) | 20.17 | 20.53 | 20.39 | 20.59 | 17.18 | 17.13 |
| Number of Blow count, N | 38 | 26 | 21 | 16 | ------ | ------ |
| Water content, W (%) | 98.11 | 99.47 | 103.35 | 109.13 | 40.44 | 40.37 |
| Liquid Limit, % | 102.58 | PI, % | 62.17 | PL, average,% | | 40.40 |

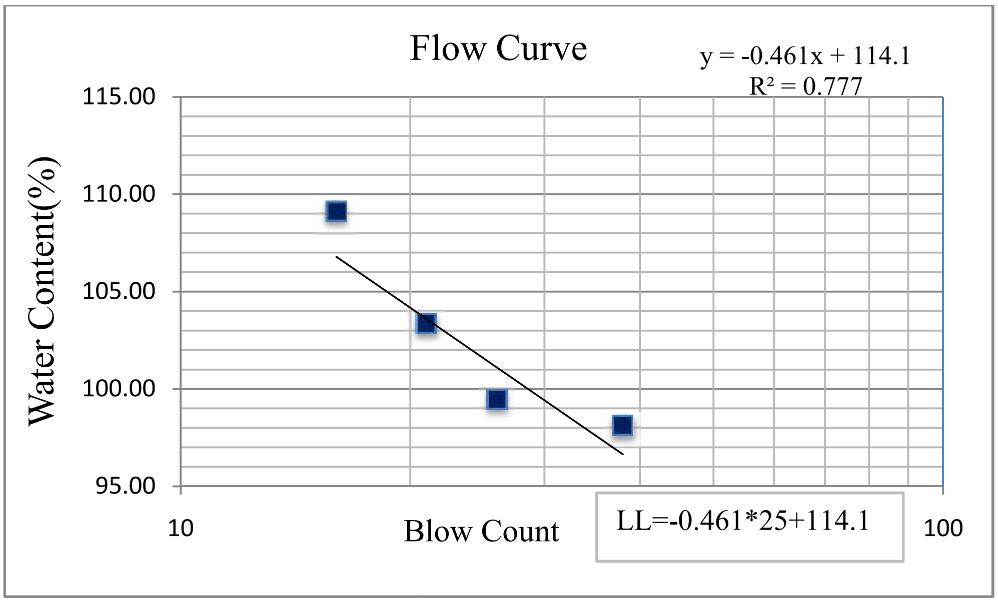


Figure A- 10 Flow curve of Bole site sample at 2.5m depth

Table A- 11 Data sheet of liquid limit and plastic limit for CMC site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | 98 | 77 | B01 | 85 | 101 | 8 |
| Weight of can, Wc (g) | 15.58 | 15.47 | 15.57 | 15.84 | 11.62 | 15.70 |
| Weight of can with wet soil, Ww (g) | 21.12 | 24.99 | 27.17 | 25.14 | 13.45 | 17.68 |
| Weight of can with dry soil, Wd (g) | 18.26 | 20.09 | 21.27 | 20.50 | 12.90 | 17.09 |
| Number of Blow count, N | 17.00 | 21.00 | 26.00 | 34.00 | ------ | ------ |
| Water content, W (%) | 106.93 | 105.92 | 103.64 | 99.73 | 43.06 | 42.76 |
| Liquid Limit, % | 103.78 | PI, % | 60.87 | PL, average,% | | 42.91 |

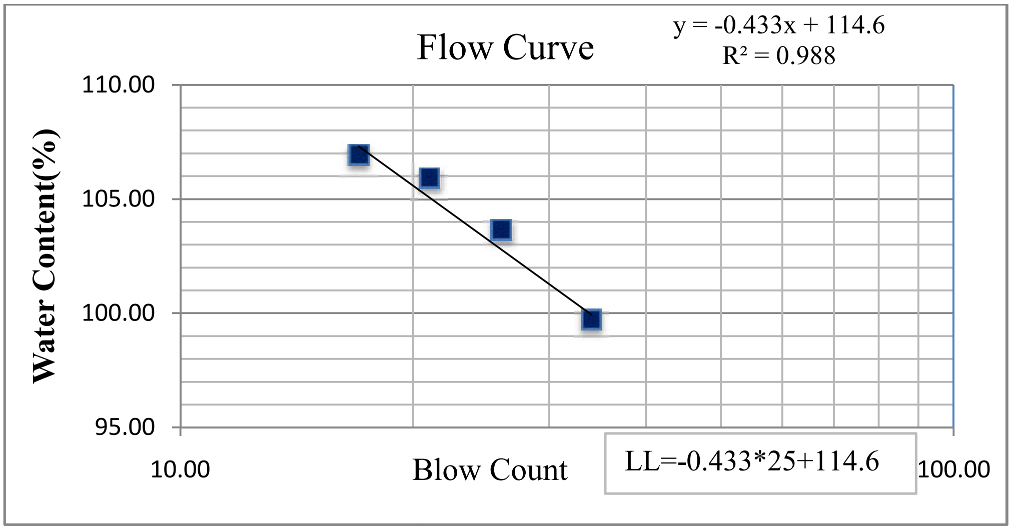


Figure A- 11 Flow curve of CMC site sample at 1.5m depth

Table A- 12 Data sheet of liquid limit and plastic limit for CMC site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | A1 | 100 | 1-A | 31 | D4 | D31 |
| Weight of can, Wc (g) | 15.59 | 15.45 | 15.29 | 15.44 | 15.95 | 15.46 |
| Weight of can with wet soil, Ww (g) | 22.65 | 25.04 | 26.41 | 26.76 | 18.72 | 17.54 |
| Weight of can with dry soil, Wd (g) | 18.98 | 19.90 | 20.52 | 20.84 | 17.90 | 16.92 |
| Number of Blow count, N | 39.00 | 18.00 | 23.00 | 26.00 | ------ | ------ |
| Water content, W (%) | 108.38 | 115.41 | 112.86 | 109.63 | 42.13 | 41.63 |
| Liquid Limit, % | 112.03 | PI, % | 70.14 | PL, average,% | | 41.88 |

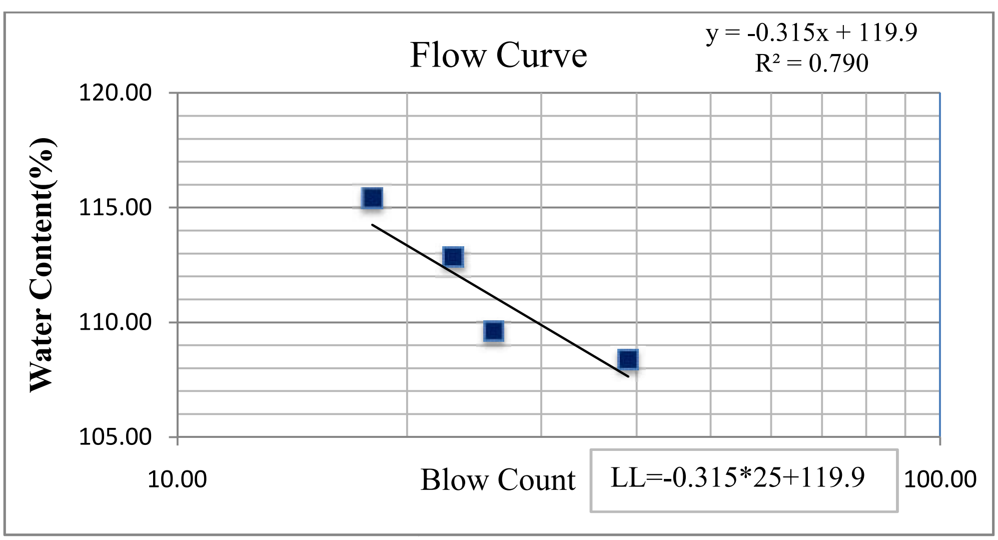


Figure A- 12 Flow curve of CMC site sample at 2.5m depth

Table A- 13 Data sheet of liquid limit and plastic limit for Emperial site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | 45 | 56 | D22 | 40 | 54 | A-16 |
| Weight of can, Wc (g) | 15.46 | 15.82 | 15.75 | 15.32 | 15.85 | 14.54 |
| Weight of can with wet soil, Ww (g) | 25.54 | 23.90 | 24.03 | 28.60 | 19.34 | 17.97 |
| Weight of can with dry soil, Wd (g) | 20.46 | 19.85 | 19.80 | 21.84 | 18.37 | 17.02 |
| Number of Blow count, N | 28.00 | 32.00 | 18.00 | 24.00 | ------ | ------ |
| Water content, W (%) | 101.75 | 100.80 | 104.79 | 103.52 | 38.45 | 38.16 |
| Liquid Limit, % | 102.80 | PI, % | 64.49 | PL, average,% | | 38.31 |

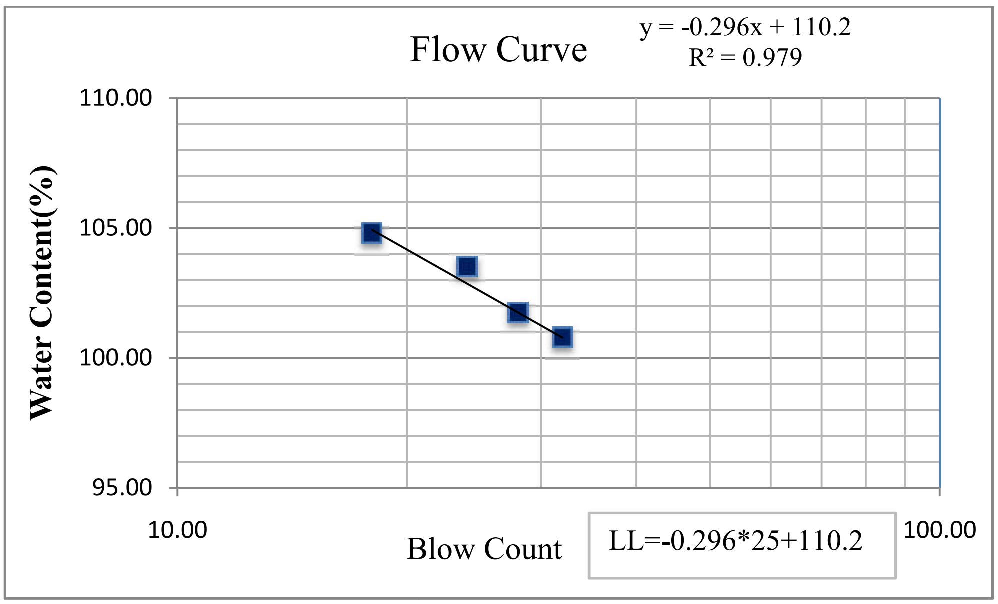


Figure A- 13 Flow curve of Emperial site sample at 1.5m depth

Table A- 14 Data sheet of liquid limit and plastic limit for Emperial site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | C-21 | D-5 | D-15 | H-3 | D-24 | A2 |
| Weight of can, Wc (g) | 14.21 | 15.70 | 15.78 | 15.10 | 15.48 | 11.49 |
| Weight of can with wet soil, Ww (g) | 24.09 | 25.12 | 26.15 | 29.16 | 19.13 | 15.50 |
| Weight of can with dry soil, Wd (g) | 19.03 | 20.36 | 20.78 | 21.79 | 18.08 | 14.38 |
| Number of Blow count, N | 27 | 33 | 23 | 13 | ------ | ------ |
| Water content, W (%) | 104.95 | 101.82 | 107.08 | 110.13 | 40.49 | 38.70 |
| Liquid Limit, % | 105.53 | PI, % | 65.93 | PL, average,% | | 39.59 |

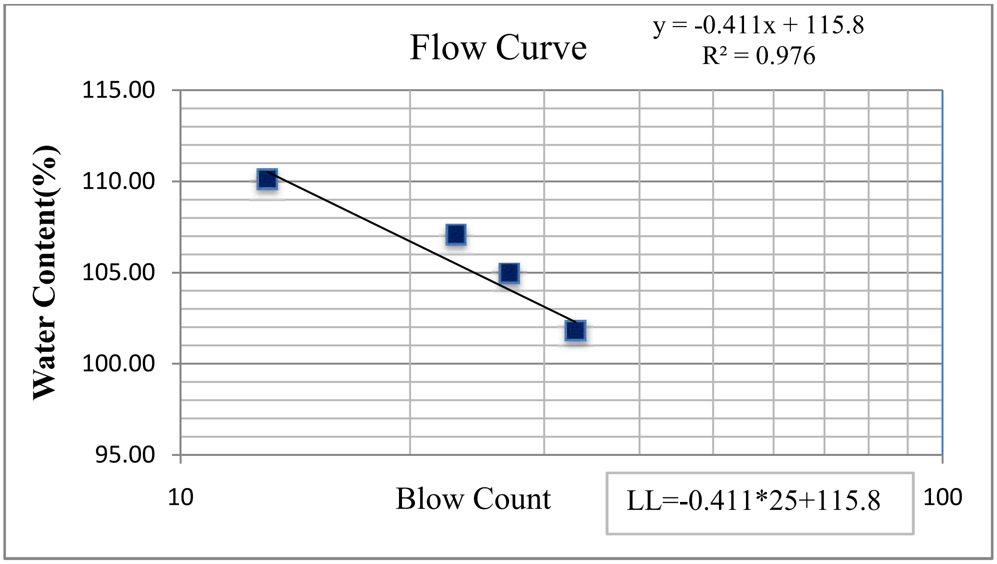


Figure A- 14 Flow curve of Emperial site sample at 2.5m depth

Table A- 15 Data sheet of liquid limit and plastic limit for Hayahulet site sample at 1.5m depth

| Depth=1.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | 19 | D21 | D19 | A-4 | H4 | 107 |
| Weight of can, Wc (g) | 15.62 | 14.29 | 15.48 | 15.61 | 15.69 | 15.60 |
| Weight of can with wet soil, Ww (g) | 27.07 | 31.90 | 33.89 | 32.04 | 20.80 | 23.66 |
| Weight of can with dry soil, Wd (g) | 21.63 | 23.33 | 24.82 | 23.81 | 19.38 | 21.46 |
| Number of Blow count, N | *33* | *28* | 23 | *17* | ------ | ------ |
| Water content, W (%) | 90.55 | 94.75 | 97.09 | 100.41 | 38.33 | 37.48 |
| Liquid Limit, % | 95.80 | PI, % | 57.89 | PL, average,% | | 37.91 |

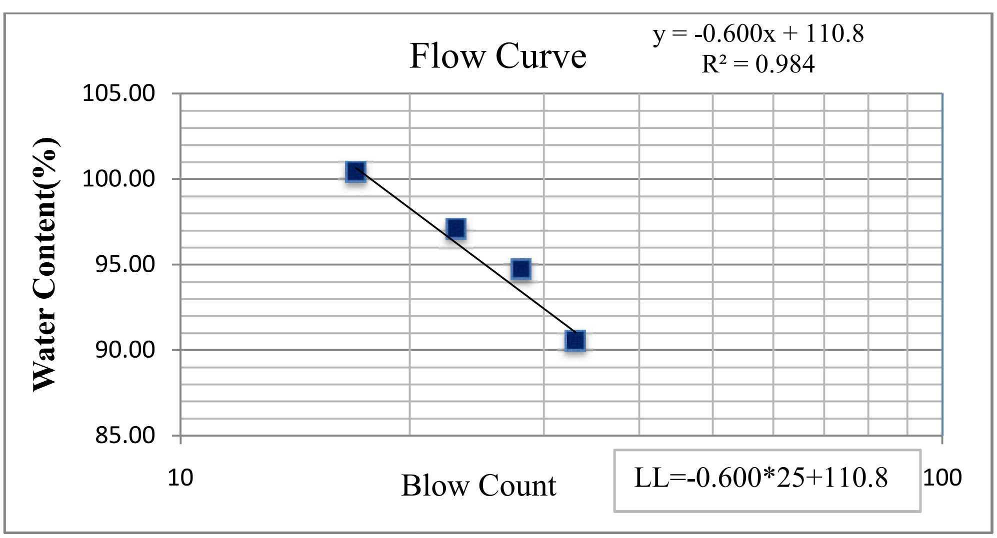


Figure A- 15 Flow curve of Hayahulet site sample at 1.5m depth

Table A- 16 Data sheet of liquid limit and plastic limit for Hayahulet site sample at 2.5m depth

| Depth=2.5m | Liquid Limit | | | | Plastic Limit | |
|---|---|---|---|---|---|---|
| Trial number | 1 | 2 | 3 | 4 | 1 | 2 |
| Can No | D-15 | 100 | D12 | D31 | D-4 | A-29 |
| Weight of can, Wc (g) | 15.77 | 15.45 | 15.70 | 15.45 | 15.95 | 15.35 |
| Weight of can with wet soil, Ww (g) | 30.11 | 29.66 | 30.62 | 30.21 | 26.52 | 27.27 |
| weight of can with dry soil, Wd (g) | 23.35 | 22.86 | 23.34 | 22.87 | 23.59 | 24.04 |
| Number of Blow count, N | 32 | 28 | 22 | 15 | ------ | ------ |
| Water content, W (%) | 89.08 | 91.82 | 95.20 | 98.91 | 38.15 | 36.97 |
| Liquid Limit, % | 93.30 | PI, % | 55.74 | PL, average,% | | 37.56 |

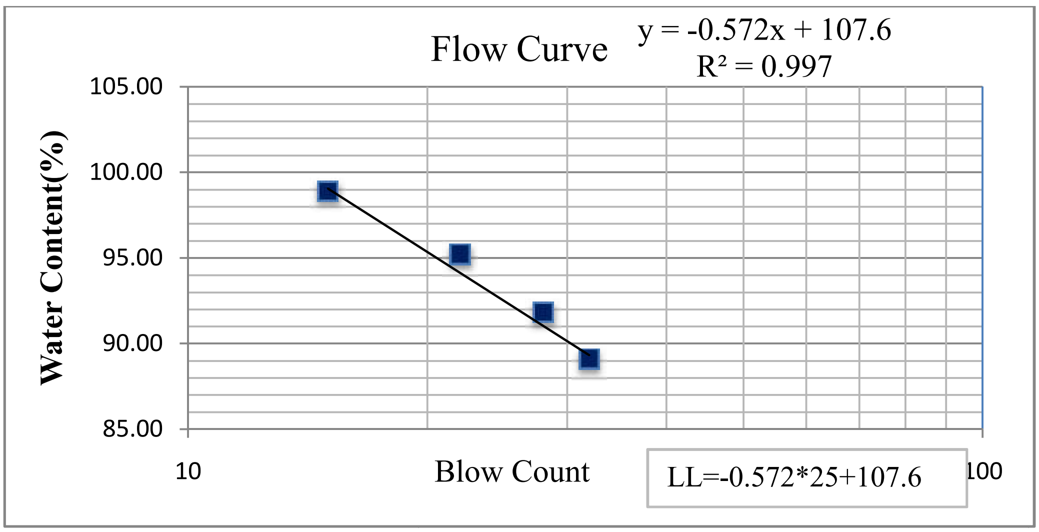


Figure A- 16 Flow curve of Hayahulet site sample at 2.5m depth

Table A- 17 Soil finer than sieve no 200($P_{200}$) for Kolfe site sample

| Location: Kolfe Area | Job ref. | Thesis |
|---|---|---|
| Test Method: ASTM D1140 Method A | Test pit no. | #1 |
| Depth | 1.5m | 2.5m |
| Weight of total oven dried sample, gm | 300 | 300 |
| Wt retained on sieve 200(oven dried),gm | 2.76 | 4.08 |
| P200 (%) | 99.08 | 98.64 |

Table A- 18 Soil finer than sieve no 200($P_{200}$) for Addisu Gebeya site sample

| Location: Addisu Gebeya Area | Job ref. | Thesis |
|---|---|---|
| Test Method: ASTM D1140 Method A | Test pit no. | #1 |
| Depth | 1.5m | 2.5m |
| Weight of total oven dried sample, gm | 300 | 300 |
| Wt retained on sieve 200(oven dried),gm | 6.66 | 7.47 |
| P200 (%) | 97.78 | 97.51 |

Table A- 19 Soil finer than sieve no 200($P_{200}$) for Aweliya site sample

| Location: Aweliya Area | Job ref. | Thesis |
|---|---|---|
| Test Method: ASTM D1140 Method A | Test pit no. | #1 |
| Depth | 1.5m | 2.5m |
| Weight of total oven dried sample, gm | 300 | 300 |
| Wt retained on sieve 200(oven dried),gm | 17.47 | 20.56 |
| P200 (%) | 94.18 | 93.15 |

Table A- 20 Soil finer than sieve no 200($P_{200}$) for Shegole site sample

| Location: Shegole Area | Job ref. | Thesis |
|---|---|---|
| Test Method: ASTM D1140 Method A | Test pit no. | #1 |
| Depth | 1.5m | 2.5m |
| Weight of total oven dried sample, gm | 300 | 300 |
| Wt retained on sieve 200(oven dried),gm | 5.83 | 9.39 |
| P200 (%) | 98.06 | 96.87 |

Table A- 21 Soil finer than sieve no 200(P200) for Bole site sample

| Location: Bole Area | Job ref. | Thesis |
|---|---|---|
| Test Method: ASTM D1140 Method B | Test pit no. | #1 |
| Depth | 1.5m | 2.5m |
| Can No | 23 | 62 |
| Wc | 15.63 | 15.63 |
| Wc+wet soil | 73.12 | 84.25 |
| Wt C+oven dried soil | 57.57 | 65.40 |
| Woven dried soil | 41.94 | 49.77 |
| Water content | 37.08 | 37.86 |
| Wt of wet soil used for washing | 330 | 350.00 |
| Weight of total oven dried sample, gm | 207.64 | 217.47 |
| Wt retained on sieve 200(oven dried),gm | 2.43 | 0.41 |
| P200 (%) | 98.83 | 99.81 |

Table A- 22 Soil finer than sieve no 200(P200) for CMC site sample

| Location: CMC Area<br>Test Method: ASTM D1140 Method B | Job ref.<br>Test pit no. | Thesis<br>#1 |
|---|---|---|
| Depth | 1.5m | 2.5m |
| Can No | 34 | B7 |
| Wc | 5.36 | 5.29 |
| Wc+wet soil | 95.00 | 96.00 |
| Wt C+oven dried soil | 72.13 | 70.90 |
| Woven dried soil | 66.78 | 65.61 |
| Water content | 34.25 | 38.26 |
| Wt of wet soil used for washing | 360.00 | 360.00 |
| Weight of total oven dried sample, gm | 236.72 | 222.28 |
| Wt retained on sieve 200(oven dried),gm | 3.64 | 16.34 |
| P200(%) | 98.46 | 92.65 |

Table A- 23 Soil finer than sieve no 200(P200) for Emperial site sample

| Location: Emperial Area<br>Test Method: ASTM D1140 Method B | Job ref.<br>Test pit no. | Thesis<br>#1 |
|---|---|---|
| Depth | 1.5m | 2.5m |
| Can No | B7 | 88 |
| Wc | 5.29 | 5.21 |
| Wc+wet soil | 113.00 | 112.00 |
| Wt C+oven dried soil | 75.66 | 82.86 |
| Woven dried soil | 70.37 | 77.65 |
| Water content | 53.06 | 37.53 |
| Wt of wet soil used for washing | 459 | 550.00 |
| Weight of total oven dried sample,gm | 215.44 | 343.60 |
| Wt retained on sieve 200(oven dried),gm | 9.49 | 9.52 |
| P200(%) | 95.59 | 97.23 |

Table A- 24 Soil finer than sieve no 200(P200) for Hayahulet site sample

| Location: Hayahulet (22) Area<br>Test Method: ASTM D1140 Method B | Job ref.<br>Test pit no. | Thesis<br>#1 |
|---|---|---|
| Depth | 1.5m | 2.5m |
| Can No | 34 | B7 |
| Wc | 5.36 | 5.29 |
| Wc+wet soil | 76.00 | 75.00 |
| Wt C+oven dried soil | 57.65 | 59.12 |
| Woven dried soil | 52.29 | 53.83 |
| Water content | 35.09 | 29.50 |
| Wt of wet soil used for washing | 350 | 350.00 |
| Weight of total oven dried sample, gm | 227.18 | 246.75 |
| Wt retained on sieve 200(oven dried),gm | 13.02 | 8.41 |
| P200(%) | 94.27 | 96.59 |

Table A- 25 Data sheet for sieve analysis test of Kolfe site sample

Total mass of sample=300gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431.00 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389.00 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378.00 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355.00 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313.00 | 313.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 40 | 0.425 | 291.00 | 291.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 50 | 0.3 | 287.00 | 287.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 100 | 0.15 | 268.00 | 270.00 | 2.00 | 0.67 | 0.67 | 99.33 |
| 200 | 0.075 | 259.00 | 261.08 | 2.08 | 0.69 | 1.36 | 98.64 |
| pan | | 240.00 | 535.92 | 295.92 | 98.64 | 100 | ------ |

Table A- 26 Hydrometer analysis for Kolfe site sample

| Location: Kolfe area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #1 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.75 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0315 | 17.3 | 0.0032 | 1.0283 | 7.97 | 0.0137 | 0.0547 | 88.82 |
| 1 | 1.0313 | 17.2 | 0.0033 | 1.0280 | 8.02 | 0.0137 | 0.0389 | 88.13 |
| 2 | 1.0310 | 17.0 | 0.0033 | 1.0277 | 8.10 | 0.0138 | 0.0277 | 87.06 |
| 5 | 1.0305 | 16.9 | 0.0033 | 1.0272 | 8.23 | 0.0138 | 0.0177 | 85.42 |
| 8 | 1.0303 | 17.0 | 0.0033 | 1.0270 | 8.29 | 0.0138 | 0.0140 | 84.86 |
| 15 | 1.0295 | 16.9 | 0.0033 | 1.0262 | 8.50 | 0.0138 | 0.0104 | 82.28 |
| 30 | 1.0285 | 17.1 | 0.0033 | 1.0252 | 8.76 | 0.0137 | 0.0074 | 79.26 |
| 60 | 1.0278 | 17.7 | 0.0032 | 1.0246 | 8.95 | 0.0136 | 0.0053 | 77.44 |
| 120 | 1.0260 | 18.0 | 0.0031 | 1.0229 | 9.42 | 0.0136 | 0.0038 | 71.97 |
| 240 | 1.0251 | 19.2 | 0.0029 | 1.0222 | 9.66 | 0.0134 | 0.0027 | 69.90 |
| 480 | 1.0248 | 17.2 | 0.0033 | 1.0215 | 9.74 | 0.0137 | 0.0020 | 67.70 |
| 1440 | 1.0235 | 18.0 | 0.0031 | 1.0204 | 10.08 | 0.0136 | 0.0011 | 64.11 |

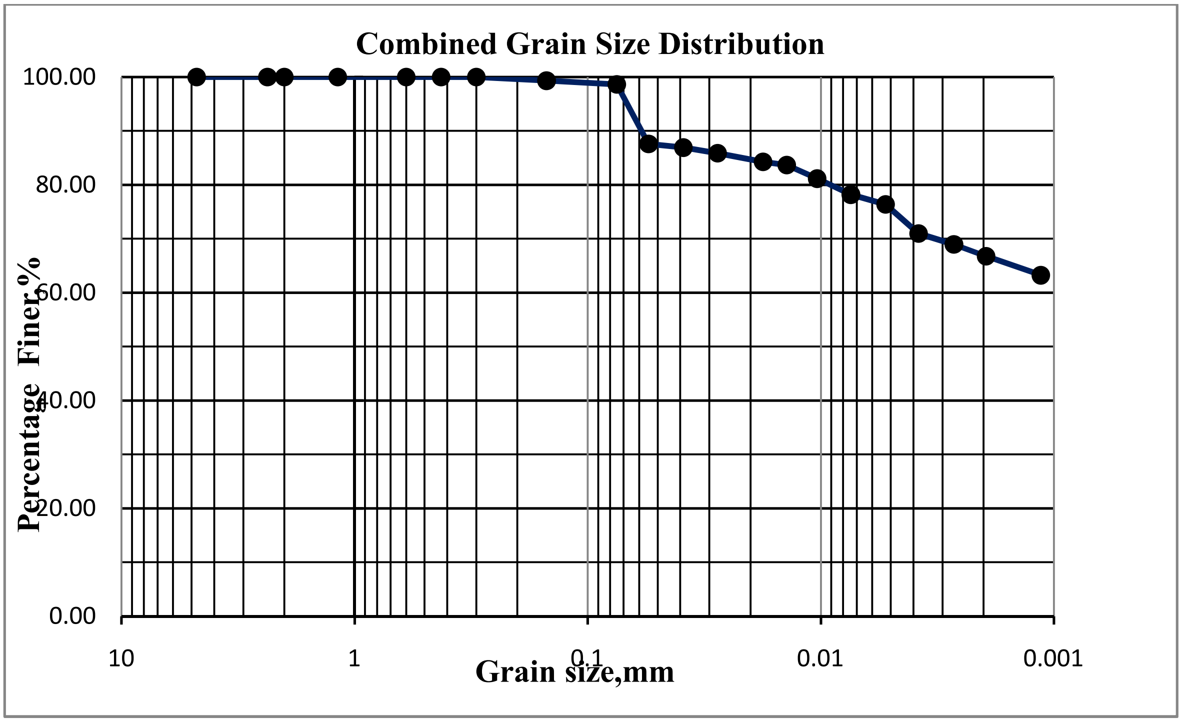


Figure A- 17 Combined grain size distribution curve for Kolfe site sample

Table A- 27 Data sheet for sieve analysis test of Addisu Gebeya site sample

Total mass of sample=300gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431.0 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389.0 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378.0 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355.0 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313.0 | 313.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 40 | 0.425 | 291.0 | 291.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 50 | 0.3 | 287.0 | 289.00 | 2.00 | 0.67 | 0.67 | 99.33 |
| 100 | 0.15 | 268.0 | 269.00 | 1.00 | 0.33 | 1.00 | 99.00 |
| 200 | 0.075 | 259.0 | 263.45 | 4.45 | 1.48 | 2.48 | 97.52 |
| pan | | 240.0 | 532.50 | 292.50 | 97.52 | 100.00 | ------ |

Table A- 28 Hydrometer analysis for Addisu Gebeya site sample

| Location: Addisu Gebeya area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #2 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.72 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0325 | 16.6 | 0.00338 | 1.0291 | 7.70 | 0.01395 | 0.05476 | 92.10 |
| 1 | 1.0320 | 16.0 | 0.0035 | 1.0285 | 7.84 | 0.01406 | 0.03936 | 90.14 |
| 2 | 1.0312 | 16.2 | 0.00346 | 1.0277 | 8.05 | 0.01402 | 0.02813 | 87.74 |
| 5 | 1.0300 | 16.4 | 0.00342 | 1.0266 | 8.36 | 0.01399 | 0.01809 | 84.07 |
| 8 | 1.0293 | 16.1 | 0.00348 | 1.0258 | 8.55 | 0.01404 | 0.01452 | 81.66 |
| 15 | 1.0275 | 16.2 | 0.00346 | 1.0240 | 9.03 | 0.01402 | 0.01088 | 76.03 |
| 30 | 1.0263 | 16.5 | 0.0034 | 1.0229 | 9.34 | 0.01397 | 0.00780 | 72.43 |
| 60 | 1.0247 | 16.5 | 0.0034 | 1.0213 | 9.77 | 0.01397 | 0.00564 | 67.37 |
| 120 | 1.0235 | 17.2 | 0.00326 | 1.0202 | 10.08 | 0.01384 | 0.00401 | 64.01 |
| 240 | 1.0221 | 18.7 | 0.00296 | 1.0191 | 10.45 | 0.01359 | 0.00284 | 60.54 |
| 480 | 1.0213 | 20.0 | 0.0027 | 1.0186 | 10.67 | 0.01336 | 0.00199 | 58.83 |
| 1440 | 1.0200 | 18.6 | 0.00298 | 1.0170 | 11.01 | 0.0136 | 0.00119 | 53.83 |

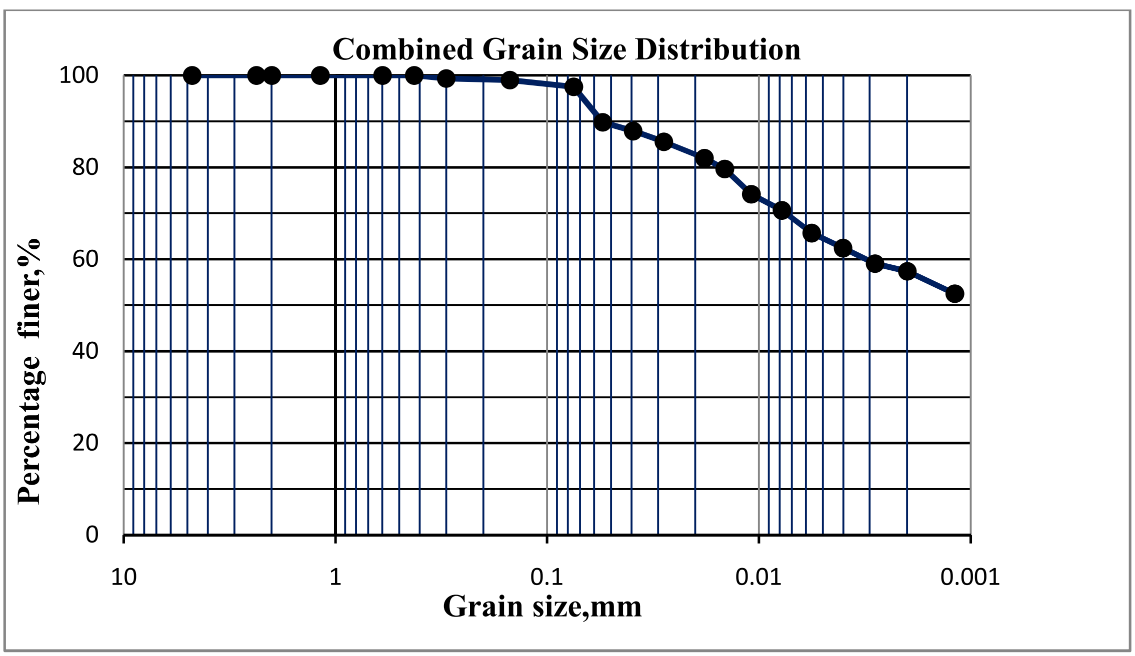


Figure A- 18 Combined grain size distribution curve for Addisu Gebeya site sample

Table A- 29 Data sheet for sieve analysis test of Aweliya site sample

Total mass of sample=300gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431.00 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389.00 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378.00 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355.00 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313.00 | 315.00 | 2.00 | 0.67 | 0.67 | 99.33 |
| 40 | 0.425 | 291.00 | 298.00 | 7.00 | 2.33 | 3.00 | 97.00 |
| 50 | 0.3 | 287.00 | 292.00 | 5.00 | 1.67 | 4.67 | 95.33 |
| 100 | 0.15 | 268.00 | 269.00 | 1.00 | 0.33 | 5.00 | 95.00 |
| 200 | 0.075 | 259.00 | 264.50 | 5.50 | 1.83 | 6.84 | 93.16 |
| pan | | 240.00 | 519.40 | 279.40 | 93.16 | 100.00 | ------ |

Table A- 30 Hydrometer analysis for Aweliya site sample

| Location: Aweliya area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #3 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.69 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0346 | 17.4 | 0.00322 | 1.0314 | 7.15 | 0.01410 | 0.0533 | 99.90 |
| 1 | 1.0343 | 17 | 0.0033 | 1.0310 | 7.23 | 0.01417 | 0.03809 | 98.69 |
| 2 | 1.0337 | 17 | 0.0033 | 1.0304 | 7.39 | 0.01417 | 0.02723 | 96.78 |
| 5 | 1.0335 | 16.9 | 0.00332 | 1.0302 | 7.44 | 0.01419 | 0.01731 | 96.08 |
| 8 | 1.0319 | 16.9 | 0.00332 | 1.0286 | 7.86 | 0.01419 | 0.01406 | 90.98 |
| 15 | 1.0308 | 17 | 0.0033 | 1.0275 | 8.15 | 0.01417 | 0.01045 | 87.54 |
| 30 | 1.0293 | 17.3 | 0.00324 | 1.0261 | 8.55 | 0.01412 | 0.00754 | 82.96 |
| 60 | 1.0277 | 17.4 | 0.00322 | 1.0245 | 8.97 | 0.01410 | 0.00545 | 77.93 |
| 120 | 1.0261 | 17.8 | 0.00314 | 1.0230 | 9.40 | 0.01403 | 0.00392 | 73.09 |
| 240 | 1.0246 | 19.2 | 0.00286 | 1.0217 | 9.79 | 0.01379 | 0.00278 | 69.21 |
| 480 | 1.0230 | 20.1 | 0.00268 | 1.0203 | 10.22 | 0.01363 | 0.00199 | 64.69 |
| 1440 | 1.0220 | 20.8 | 0.00254 | 1.0195 | 10.48 | 0.01351 | 0.00115 | 61.95 |

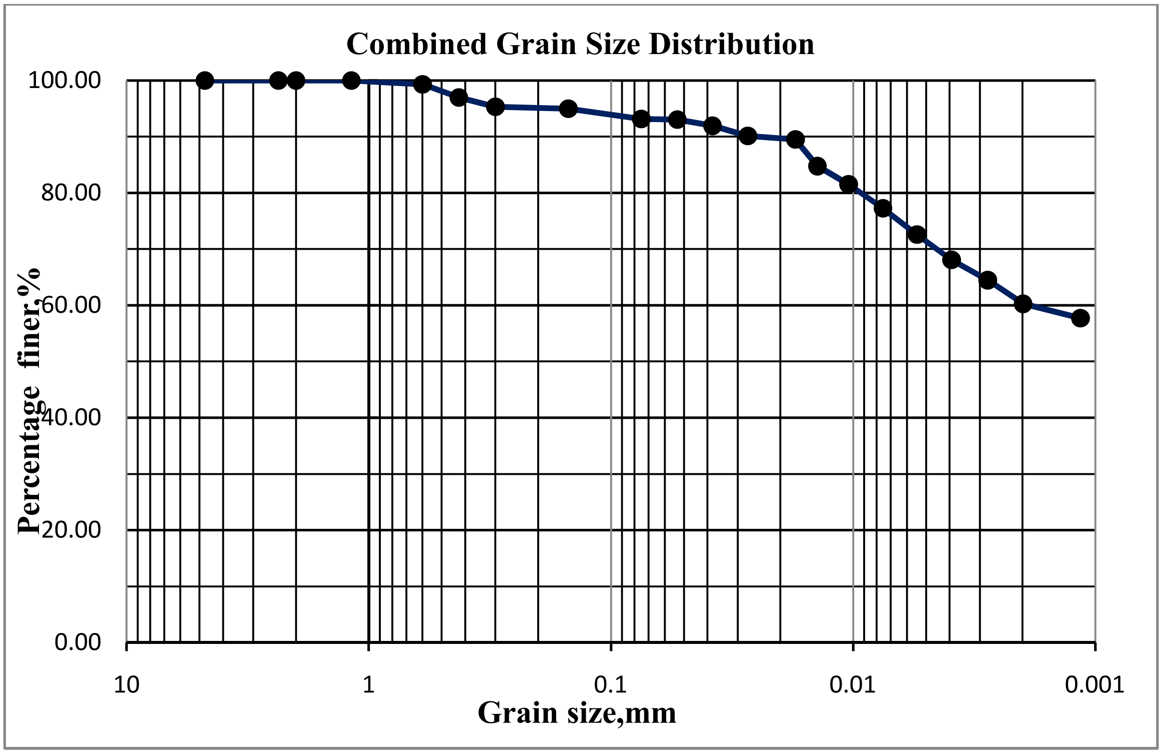


Figure A- 19 Combined grain size distribution curve for Aweliya site sample

Table A- 31 Data sheet for sieve analysis test of Shegole site sample

Total mass of sample=300gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431.00 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389.00 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378.00 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355.00 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313.00 | 313.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 40 | 0.425 | 291.00 | 293.50 | 2.50 | 0.83 | 0.83 | 99.17 |
| 50 | 0.3 | 287.00 | 289.00 | 2.00 | 0.67 | 1.50 | 98.50 |
| 100 | 0.15 | 268.00 | 269.00 | 1.00 | 0.33 | 1.83 | 98.17 |
| 200 | 0.075 | 259.00 | 262.80 | 3.80 | 1.27 | 3.10 | 96.90 |
| pan | | 240.00 | 530.60 | 290.60 | 96.90 | 100.00 | ------ |

Table A- 32 Hydrometer analysis for Shegole site sample

| Location: Shegole area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #4 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.79 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0328 | 18.4 | 0.00302 | 1.0298 | 7.62 | 0.01333 | 0.0520 | 91.75 |
| 1 | 1.0324 | 18.6 | 0.00298 | 1.0294 | 7.73 | 0.01329 | 0.0370 | 90.65 |
| 2 | 1.0321 | 18.6 | 0.00298 | 1.0291 | 7.81 | 0.01329 | 0.0263 | 89.72 |
| 5 | 1.0315 | 18.8 | 0.00294 | 1.0286 | 7.97 | 0.01326 | 0.0167 | 88.00 |
| 8 | 1.0310 | 19 | 0.0029 | 1.0281 | 8.10 | 0.01323 | 0.0133 | 86.58 |
| 15 | 1.0300 | 18.9 | 0.00292 | 1.0271 | 8.36 | 0.01325 | 0.0099 | 83.44 |
| 30 | 1.0290 | 19.3 | 0.00284 | 1.0262 | 8.63 | 0.01318 | 0.0071 | 80.60 |
| 60 | 1.0276 | 19.4 | 0.00282 | 1.0248 | 9.00 | 0.01317 | 0.0051 | 76.35 |
| 120 | 1.0270 | 19.7 | 0.00276 | 1.0242 | 9.16 | 0.01312 | 0.0036 | 74.69 |
| 240 | 1.0252 | 21.9 | 0.00232 | 1.0229 | 9.63 | 0.01291 | 0.0026 | 70.50 |
| 480 | 1.0240 | 23.5 | 0.002 | 1.0220 | 9.95 | 0.01291 | 0.0019 | 67.78 |
| 1440 | 1.0233 | 19.6 | 0.00278 | 1.0205 | 10.14 | 0.01313 | 0.0011 | 63.22 |

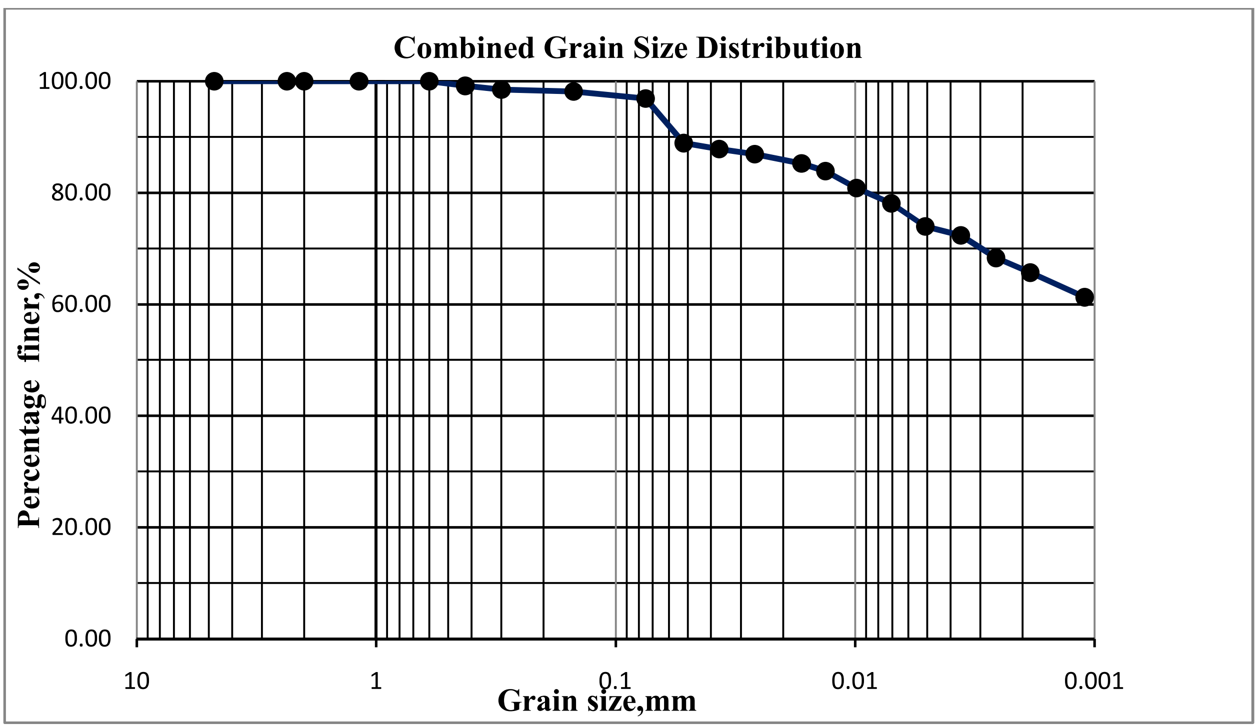


Figure A- 20 Combined grain size distribution curve for Shegole site sample

Table A- 33 Data sheet for sieve analysis test of Bole site sample

Total mass of sample=217.4gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431.00 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389.00 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378.00 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355.00 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313.00 | 313.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 40 | 0.425 | 291.00 | 291.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 50 | 0.3 | 287.00 | 287.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 100 | 0.15 | 268.00 | 268.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 200 | 0.075 | 259.00 | 259.40 | 0.40 | 0.18 | 0.18 | 99.82 |
| pan | | 240.00 | 457.00 | 217.00 | 99.82 | 100.00 | ------ |

Table A- 34 Hydrometer analysis for Bole site sample

| Location: Bole area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #5 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.51 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0315 | 18.4 | 0.00302 | 1.0285 | 7.97 | 0.01455 | 0.0581 | 94.68 |
| 1 | 1.0308 | 17.8 | 0.00314 | 1.0277 | 8.15 | 0.01466 | 0.0419 | 91.96 |
| 2 | 1.0307 | 18.1 | 0.00308 | 1.0276 | 8.18 | 0.0146 | 0.0295 | 91.82 |
| 5 | 1.0306 | 17.7 | 0.00316 | 1.0274 | 8.21 | 0.01468 | 0.0188 | 91.22 |
| 8 | 1.0303 | 17.5 | 0.0032 | 1.0271 | 8.29 | 0.01472 | 0.0150 | 90.09 |
| 15 | 1.0298 | 18 | 0.0031 | 1.0267 | 8.42 | 0.01462 | 0.0110 | 88.76 |
| 30 | 1.0292 | 17.8 | 0.00314 | 1.0261 | 8.58 | 0.01466 | 0.0078 | 86.64 |
| 60 | 1.0288 | 18.2 | 0.00306 | 1.0257 | 8.68 | 0.01459 | 0.0055 | 85.57 |
| 120 | 1.0273 | 19.4 | 0.00282 | 1.0245 | 9.08 | 0.01437 | 0.0040 | 81.38 |
| 240 | 1.0270 | 20.7 | 0.00256 | 1.0244 | 9.16 | 0.01415 | 0.0028 | 81.25 |
| 480 | 1.0264 | 23.6 | 0.00198 | 1.0244 | 9.32 | 0.01409 | 0.0020 | 81.18 |
| 1440 | 1.0260 | 19.2 | 0.00286 | 1.0231 | 9.42 | 0.01441 | 0.0012 | 76.93 |

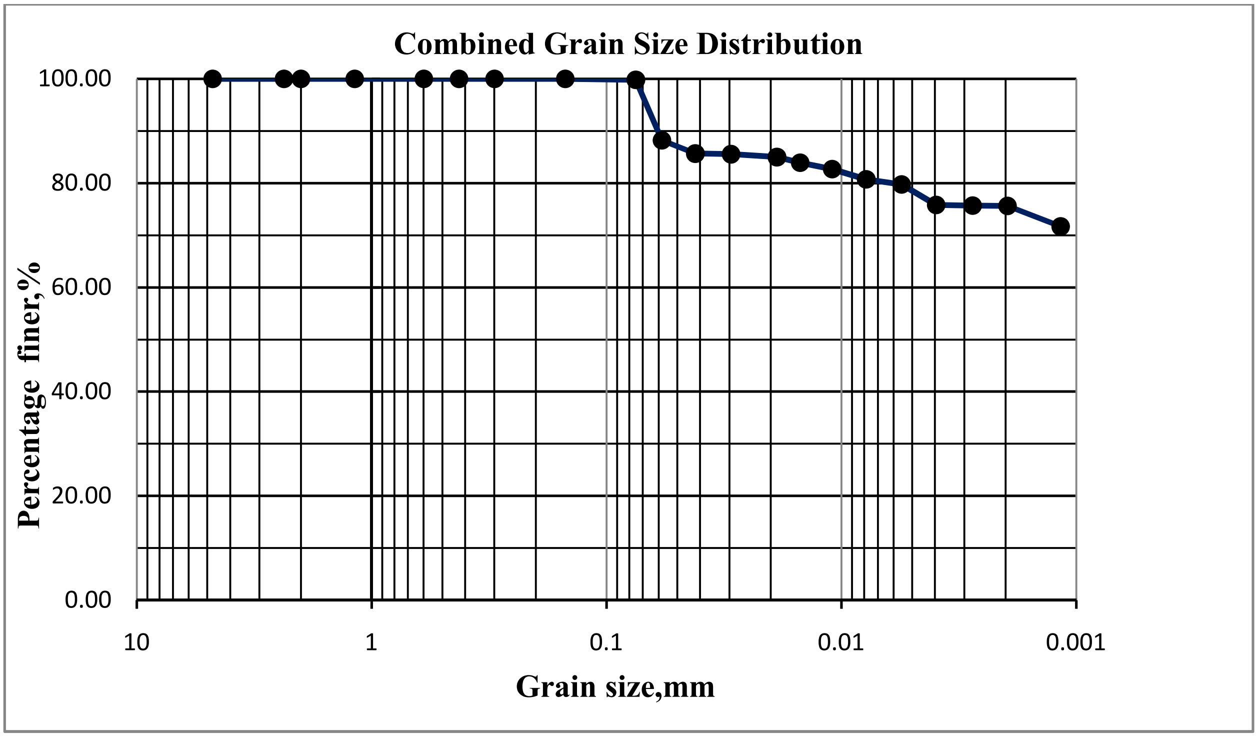


Figure A- 21 Combined grain size distribution curve for Bole site sample

Table A- 35 Data sheet for sieve analysis test of CMC site sample

Total mass of sample=222.28gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431.00 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389.00 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378.00 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355.00 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313.00 | 313.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 40 | 0.425 | 291.00 | 297.00 | 6.00 | 2.70 | 2.70 | 97.30 |
| 50 | 0.3 | 287.00 | 291.00 | 4.00 | 1.80 | 4.50 | 95.50 |
| 100 | 0.15 | 268.00 | 271.00 | 3.00 | 1.35 | 5.85 | 94.15 |
| 200 | 0.075 | 259.00 | 262.30 | 3.30 | 1.49 | 7.34 | 92.66 |
| pan | | 240.00 | 445.90 | 205.90 | 92.66 | 100.00 | ------ |

Table A- 36 Hydrometer analysis for CMC site sample

| Location: CMC area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #6 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.73 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0315 | 17.8 | 0.00314 | 1.0284 | 7.97 | 0.01370 | 0.0547 | 89.51 |
| 1 | 1.0314 | 18.1 | 0.00308 | 1.0283 | 7.99 | 0.01365 | 0.0386 | 89.38 |
| 2 | 1.0313 | 18.1 | 0.00308 | 1.0282 | 8.02 | 0.01365 | 0.0273 | 89.06 |
| 5 | 1.0312 | 18.4 | 0.00302 | 1.0282 | 8.05 | 0.01360 | 0.0173 | 88.94 |
| 8 | 1.0310 | 18.5 | 0.00300 | 1.0280 | 8.10 | 0.01358 | 0.0137 | 88.37 |
| 15 | 1.0298 | 18.4 | 0.00302 | 1.0268 | 8.42 | 0.01360 | 0.0102 | 84.52 |
| 30 | 1.0290 | 18.5 | 0.00300 | 1.0260 | 8.63 | 0.01358 | 0.0073 | 82.06 |
| 60 | 1.0282 | 19.4 | 0.00282 | 1.0254 | 8.84 | 0.01343 | 0.0052 | 80.10 |
| 120 | 1.0273 | 19.7 | 0.00276 | 1.0245 | 9.08 | 0.01338 | 0.0037 | 77.45 |
| 240 | 1.0261 | 21.3 | 0.00244 | 1.0237 | 9.40 | 0.01317 | 0.0026 | 74.67 |
| 480 | 1.0253 | 23.4 | 0.00202 | 1.0233 | 9.61 | 0.01317 | 0.0019 | 73.47 |
| 1440 | 1.0250 | 19.3 | 0.00284 | 1.0222 | 9.69 | 0.01345 | 0.0011 | 69.94 |

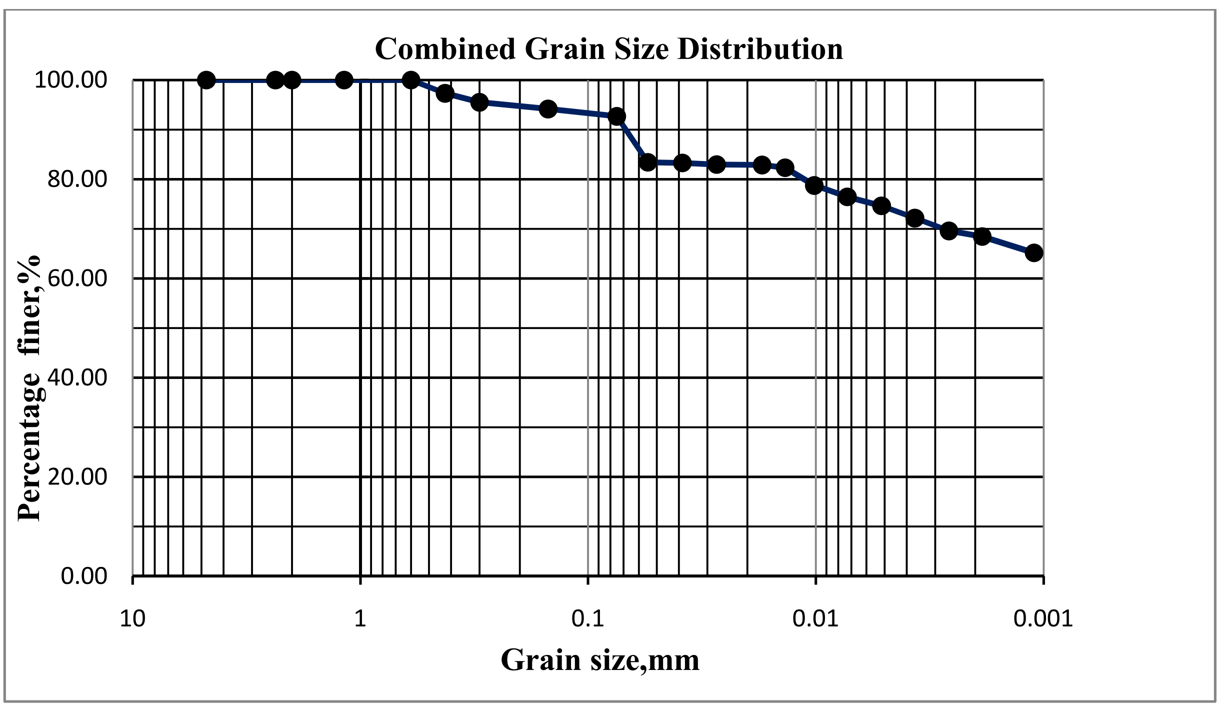


Figure A- 22 Combined grain size distribution curve for CMC site sample

Table A- 37 Data sheet for sieve analysis test of Emperial site sample

Total mass of sample=343.6gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431.00 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389.00 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378.00 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355.00 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313.00 | 313.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 40 | 0.425 | 291.00 | 291.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 50 | 0.3 | 287.00 | 290.50 | 3.50 | 1.02 | 1.02 | 98.98 |
| 100 | 0.15 | 268.00 | 272.00 | 4.00 | 1.16 | 2.18 | 97.82 |
| 200 | 0.075 | 259.00 | 261.00 | 2.00 | 0.58 | 2.77 | 97.23 |
| pan | | 240.00 | 574.00 | 334.00 | 97.23 | 100.00 | ------ |

Table A- 38 Hydrometer analysis for Emperial site sample

| Location: Emperial area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #7 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.47 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0322 | 18.0 | 0.0031 | 1.0291 | 7.78 | 0.01482 | 0.0585 | 97.79 |
| 1 | 1.032 | 17.8 | 0.00314 | 1.02886 | 7.84 | 0.01486 | 0.0416 | 96.99 |
| 2 | 1.0311 | 17.7 | 0.00316 | 1.02794 | 8.07 | 0.01488 | 0.0299 | 93.89 |
| 5 | 1.0302 | 17.9 | 0.00312 | 1.02708 | 8.31 | 0.01484 | 0.0191 | 91.00 |
| 8 | 1.0291 | 18.4 | 0.00302 | 1.02608 | 8.60 | 0.01475 | 0.0153 | 87.64 |
| 15 | 1.0278 | 18.4 | 0.00302 | 1.02478 | 8.95 | 0.01475 | 0.0114 | 83.27 |
| 30 | 1.0258 | 18.7 | 0.00296 | 1.02284 | 9.48 | 0.01469 | 0.0083 | 76.75 |
| 60 | 1.0237 | 19.0 | 0.0029 | 1.0208 | 10.03 | 0.01464 | 0.0060 | 69.90 |
| 120 | 1.022 | 20.2 | 0.00266 | 1.01934 | 10.48 | 0.01442 | 0.0043 | 64.99 |
| 240 | 1.0213 | 22.8 | 0.00214 | 1.01916 | 10.67 | 0.01428 | 0.0030 | 64.39 |
| 480 | 1.019 | 23.6 | 0.00198 | 1.01702 | 11.27 | 0.01428 | 0.0022 | 57.20 |
| 1440 | 1.017 | 20.1 | 0.00268 | 1.01432 | 11.80 | 0.01444 | 0.0013 | 48.12 |

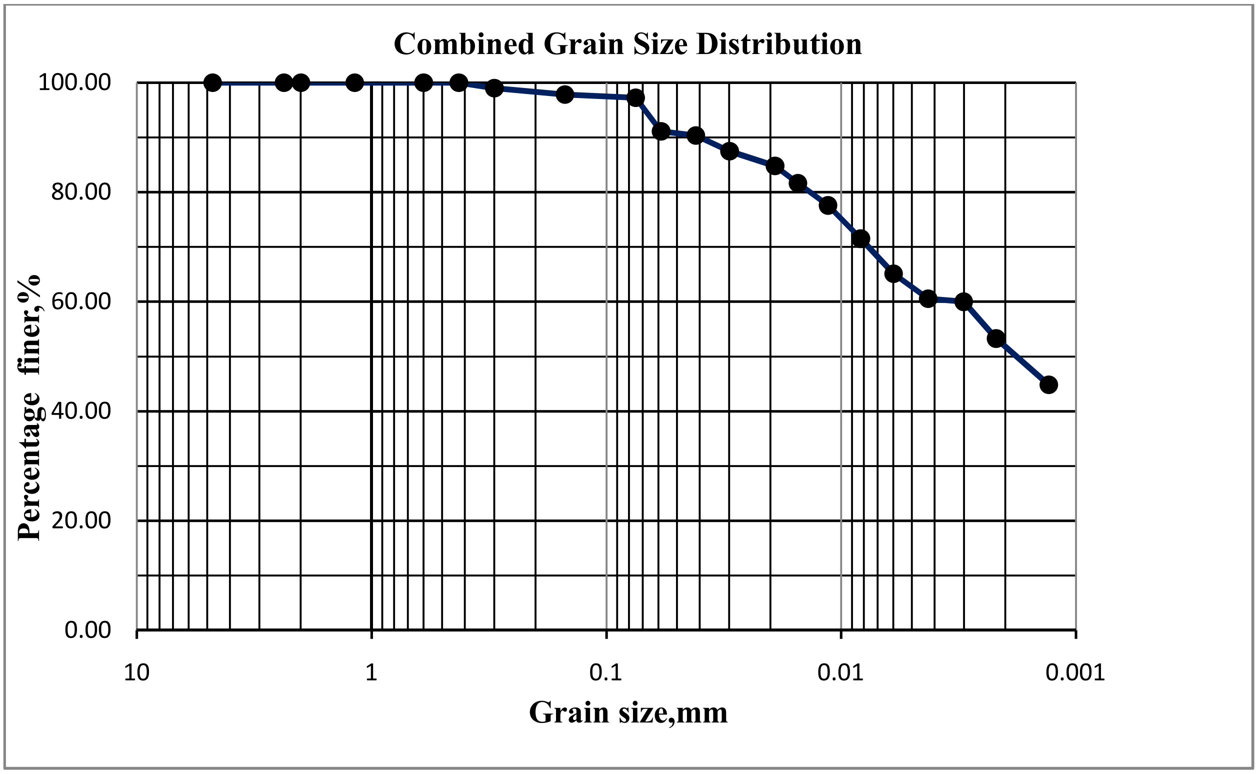


Figure A- 23 Combined grain size distribution curve for Emperial site sample

Table A- 39 Data sheet for sieve analysis test of Hayahulet site sample

Total mass of sample=246.75gm

| Sieve no | Diameter, mm | Mass of empty sieve, g | Mass of sieve+soil retained, g | Soil retained, g | Percent retained,% | Cumulative percent retained,% | Percent finer,% |
|---|---|---|---|---|---|---|---|
| 4 | 4.75 | 431 | 431.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 8 | 2.36 | 389 | 389.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 10 | 2 | 378 | 378.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 16 | 1.18 | 355 | 355.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 30 | 0.6 | 313 | 313.00 | 0.00 | 0.00 | 0.00 | 100.00 |
| 40 | 0.425 | 291 | 293.40 | 2.40 | 0.97 | 0.97 | 99.03 |
| 50 | 0.3 | 287 | 289.00 | 2.00 | 0.81 | 1.78 | 98.22 |
| 100 | 0.15 | 268 | 268.00 | 0.00 | 0.00 | 1.78 | 98.22 |
| 200 | 0.075 | 259 | 263.00 | 4.00 | 1.62 | 3.40 | 96.60 |
| pan | | 240 | 478.34 | 238.34 | 96.60 | 100.00 | ------ |

Table A- 40 Hydrometer analysis for Hayahulet site sample

| Location: Hayahulet(22) area<br>Test Method: ASTM D 422-63 | | | | | Job ref. | | Thesis | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Test pit no. | | #8 | |
| | | | | | Depth | | 2.5m | |
| | | | | | Specific Gravity | | 2.72 | |
| Elapsed Time (min) | Actual Hydrometer Reading | Test Temperature (°C) | Composite Correction | Corrected Hydrometer Reading | Effective Depth (cm) | Coefficient K | Grain Size (mm) | Percentage Finer % |
| 0.5 | 1.0310 | 17.5 | 0.00320 | 1.0278 | 8.10 | 0.0138 | 0.056 | 87.93 |
| 1 | 1.0305 | 17.8 | 0.00314 | 1.0274 | 8.23 | 0.0137 | 0.039 | 86.53 |
| 2 | 1.0300 | 17.6 | 0.00318 | 1.0268 | 8.36 | 0.0138 | 0.028 | 84.83 |
| 5 | 1.0293 | 17.7 | 0.00316 | 1.0261 | 8.55 | 0.0138 | 0.018 | 82.68 |
| 8 | 1.0285 | 17.6 | 0.00318 | 1.0253 | 8.76 | 0.0138 | 0.014 | 80.08 |
| 15 | 1.0280 | 17.8 | 0.00314 | 1.0249 | 8.89 | 0.0137 | 0.011 | 78.63 |
| 30 | 1.0266 | 18.2 | 0.00306 | 1.0235 | 9.26 | 0.0137 | 0.008 | 74.45 |
| 60 | 1.0251 | 18.5 | 0.00300 | 1.0221 | 9.66 | 0.0136 | 0.005 | 69.90 |
| 120 | 1.0245 | 19.6 | 0.00278 | 1.0217 | 9.82 | 0.0134 | 0.004 | 68.70 |
| 240 | 1.0234 | 21.8 | 0.00234 | 1.0211 | 10.11 | 0.0132 | 0.003 | 66.61 |
| 480 | 1.0225 | 22.9 | 0.00212 | 1.0204 | 10.35 | 0.0132 | 0.002 | 64.46 |
| 1440 | 1.0220 | 19.5 | 0.00280 | 1.0192 | 10.48 | 0.0134 | 0.001 | 60.73 |

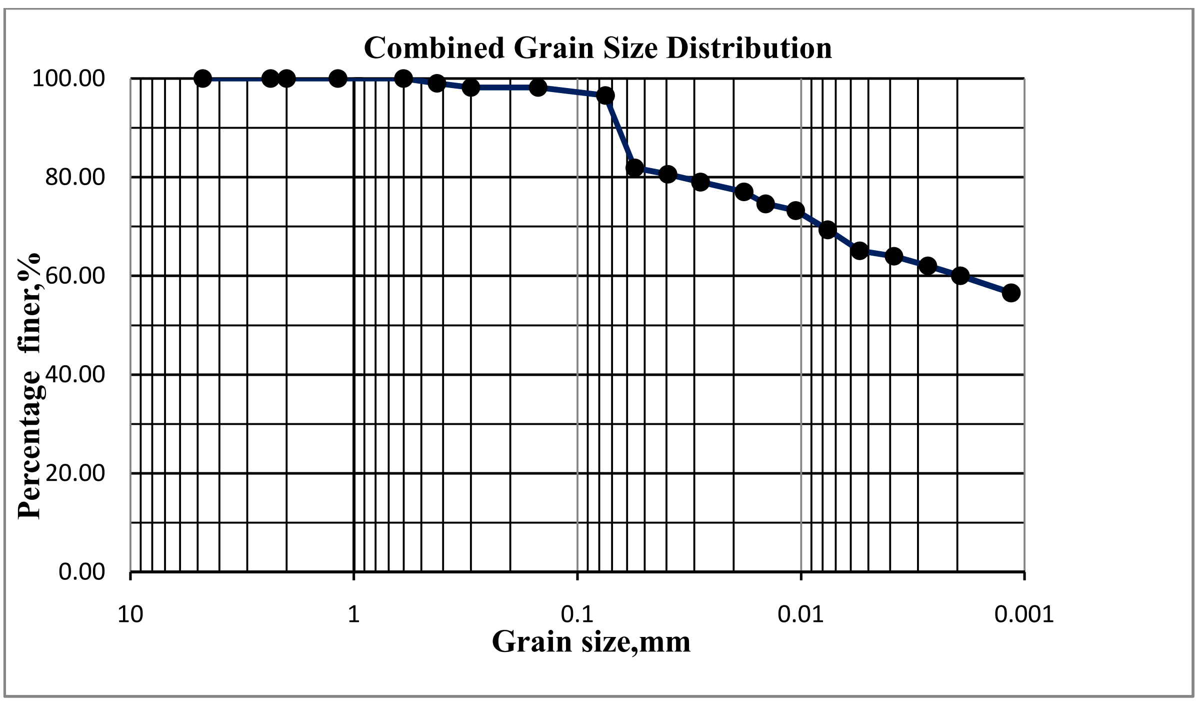


Figure A- 24 Combined grain size distribution curve for Hayahulet site sample

Table A- 41 Data sheet for specific gravity test of Kolfe site sample

| | | |
|---|---|---|
| Location: Kolfe Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #1 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P9 | P10 |
| Mass of Pycnometer(Mp),g | 49.63 | 45.83 |
| Mass of pycnometer + Water atTa (Mpw),g | 149.11 | 145.29 |
| Observed temprature of water (Ta),°c | 17.90 | 18.20 |
| Observed temprature of Water and soil solution (Tb),°c | 19.40 | 19.40 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 149.08 | 145.26 |
| Mass of pycnometer +water+soil (Mpws),g | 166.25 | 161.45 |
| Mass of oven dried soil (Mos),g | 27.00 | 25.44 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.75 | 2.75 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.75 | 2.75 |
| Average | 2.75 | |

Table A- 42 Data sheet for specific gravity test of Addisu Gebeya site sample

| | | |
|---|---|---|
| Location: Addisu Gebeya Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #1 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P9 | P10 |
| Mass of Pycnometer(Mp),g | 49.59 | 45.86 |
| Mass of pycnometer + Water atTa (Mpw),g | 149.11 | 145.29 |
| Observed temprature of water (Ta),°c | 17.00 | 16.90 |
| Observed temprature of Water and soil solution (Tb),°c | 17.30 | 17.80 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 149.10 | 145.27 |
| Mass of pycnometer +water+soil (Mpws),g | 164.89 | 161.17 |
| Mass of oven dried soil (Mos),g | 25.04 | 25.04 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.71 | 2.74 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.71 | 2.74 |
| Average | 2.72 | |

Table A- 43 Data sheet for specific gravity test of Aweliya site sample

| | | |
|---|---|---|
| Location: Aweliya Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #4 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P9 | P10 |
| Mass of Pycnometer(Mp),g | 49.59 | 45.86 |
| Mass of pycnometer + Water atTa (Mpw),g | 149.11 | 145.29 |
| Observed temprature of water (Ta),°c | 18.40 | 18.50 |
| Observed temprature of Water and soil solution (Tb),°c | 20.10 | 21.10 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 149.08 | 145.24 |
| Mass of pycnometer +water+soil (Mpws),g | 165.52 | 161.59 |
| Mass of oven dried soil (Mos),g | 26.07 | 26.14 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.71 | 2.67 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.71 | 2.67 |
| Average | 2.69 | |

Table A- 44 Data sheet for specific gravity test of Shegole site sample

| | | |
|---|---|---|
| Location: Shegole Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #4 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P3 | P13 |
| Mass of Pycnometer(Mp),g | 45.80 | 49.10 |
| Mass of pycnometer + Water atTa (Mpw),g | 145.32 | 148.52 |
| Observed temprature of water (Ta),°c | 19.00 | 19.10 |
| Observed temprature of Water and soil solution (Tb),°c | 20.20 | 20.30 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 145.29 | 148.50 |
| Mass of pycnometer +water+soil (Mpws),g | 161.64 | 164.56 |
| Mass of oven dried soil (Mos),g | 25.38 | 25.16 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.81 | 2.76 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.81 | 2.76 |
| Average | 2.79 | |

Table A- 45 Data sheet for specific gravity test of Bole site sample

| | | |
|---|---|---|
| Location: Bole Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #5 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P3 | P13 |
| Mass of Pycnometer(Mp),g | 45.80 | 49.10 |
| Mass of pycnometer + Water atTa (Mpw),g | 145.34 | 148.41 |
| Observed temprature of water (Ta),°c | 18.50 | 18.40 |
| Observed temprature of Water and soil solution (Tb),°c | 23.80 | 23.50 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 145.23 | 148.30 |
| Mass of pycnometer +water+soil (Mpws),g | 160.29 | 163.67 |
| Mass of oven dried soil (Mos),g | 25.20 | 25.34 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.49 | 2.54 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.48 | 2.54 |
| Average | 2.51 | |

Table A- 46 Data sheet for specific gravity test of CMC site sample

| | | |
|---|---|---|
| Location: CMC Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #6 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P3 | P13 |
| Mass of Pycnometer(Mp),g | 45.68 | 49.44 |
| Mass of pycnometer + Water atTa (Mpw),g | 145.32 | 148.52 |
| Observed temprature of water (Ta),°c | 18.70 | 18.60 |
| Observed temprature of Water and soil solution (Tb),°c | 21.60 | 21.80 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 145.26 | 148.46 |
| Mass of pycnometer +water+soil (Mpws),g | 161.26 | 164.52 |
| Mass of oven dried soil (Mos),g | 25.25 | 25.30 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.73 | 2.74 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.73 | 2.74 |
| Average | 2.73 | |

Table A- 47 Data sheet for specific gravity test of Emperial site sample

| | | |
|---|---|---|
| Location: Emperial Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #7 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P1 | P3 |
| Mass of Pycnometer(Mp),g | 45.31 | 45.89 |
| Mass of pycnometer + Water atTa (Mpw),g | 144.73 | 145.50 |
| Observed temprature of water (Ta),°c | 18.80 | 18.30 |
| Observed temprature of Water and soil solution (Tb),°c | 20.70 | 20.60 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 144.69 | 145.45 |
| Mass of pycnometer +water+soil (Mpws),g | 160.22 | 161.20 |
| Mass of oven dried soil (Mos),g | 26.16 | 26.32 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.46 | 2.49 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.46 | 2.49 |
| Average | 2.47 | |

Table A- 48 Data sheet for specific gravity test of Hayahulet site sample

| | | |
|---|---|---|
| Location: Hayahulet Area<br>Test: Specific Gravity<br>Test Method: ASTM D854 | Job ref. | Thesis |
| | Test pit no. | #8 |
| | Depth | 2.5m |
| Trial | #1 | #2 |
| Pycnometer number | P13 | P3 |
| Mass of Pycnometer(Mp),g | 49.10 | 45.80 |
| Mass of pycnometer + Water atTa (Mpw),g | 149.11 | 145.29 |
| Observed temprature of water (Ta),°c | 17.70 | 18.10 |
| Observed temprature of Water and soil solution (Tb),°c | 19.60 | 19.30 |
| Relative density of water at Tb,g/ml | 1.00 | 1.00 |
| Relative density of water at Ta, g/ml | 1.00 | 1.00 |
| Mass of pycnometer + Water atTb (Mpw),g | 149.07 | 145.26 |
| Mass of pycnometer +water+soil (Mpws),g | 166.46 | 161.36 |
| Mass of oven dried soil (Mos),g | 27.55 | 25.45 |
| Conversion factor K | 1.00 | 1.00 |
| Specific gravity of soil at T=Tb (G at Tb=Mos/(Mos+(Mpw at Tb-Mpws)) | 2.71 | 2.72 |
| Specific gravity of soil at T=20°c,(Gat Tb * K) | 2.71 | 2.72 |
| Average | 2.72 | |

Table A- 49 Data sheet of free swell test for Kolfe site sample

| Location: Kolfe Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #1 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume, ml | 10 | 10 |
| Final Volume, ml | 14.5 | 14 |
| Volume Change, ml | 4.5 | 4 |
| Free Swell, % | 45 | 40 |
| Average,% | 42.5 | |

Table A- 50 Data sheet of free swell test for Addisu Gebeya site sample

| Location: Addisu Gebeya Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #2 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume, ml | 10 | 10 |
| Final Volume, ml | 14 | 15.3 |
| Volume Change, ml | 4 | 5.3 |
| Free Swell, % | 40 | 53 |
| Average,% | 46.5 | |

Table A- 51 Data sheet of free swell test for Aweliya site sample

| Location: Aweliya Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #3 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume, ml | 10 | 10 |
| Final Volume, ml | 12 | 11 |
| Volume Change, ml | 2 | 1 |
| Free Swell, % | 20 | 10 |

Table A- 52 Data sheet of free swell test for Shegole site sample

| Location: Shegole Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #4 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume, ml | 10 | 10 |
| Final Volume, ml | 13.7 | 13.5 |
| Volume Change, ml | 3.7 | 3.5 |
| Free Swell, % | 37 | 35 |
| Average,% | 36 | |

Table A- 53 Data sheet of free swell test for Bole site sample

| Location: Bole Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #5 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume, ml | 10 | 10 |
| Final Volume, ml | 28 | 27 |
| Volume Change ,ml | 18 | 17 |
| Free Swell, % | 180 | 170 |
| Average,% | 175 | |

Table A- 54 Data sheet of free swell test for CMC site sample

| Location: CMC Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #6 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume ,ml | 10 | 10 |
| Final Volume, ml | 31 | 30 |
| Volume Change, ml | 21 | 20 |
| Free Swell, % | 210 | 200 |
| Average,% | 205 | |

Table A- 55 Data sheet of free swell test for Emperial site sample

| Location: Emperial Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #7 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume, ml | 10 | 10 |
| Final Volume, ml | 20.5 | 17.5 |
| Volume Change, ml | 10.5 | 7.5 |
| Free Swell, % | 105 | 75 |
| Average,% | 90 | |

Table A- 56 Data sheet of free swell test for Hayahulet site sample

| Location: Hayahulet Area<br>Test Method: ASTM D | Job ref. | Thesis |
|---|---|---|
| | Test pit no. | #8 |
| | Depth | 2.5m |
| Trial No | 1 | 2 |
| Initial Volume, ml | 10 | 10 |
| Final Volume, ml | 27 | 26 |
| Volume Change, ml | 17 | 16 |
| Free Swell, % | 170 | 160 |
| Average,% | 165 | |

Table A- 57A Data used for plotting SWCC for Kolfe sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.03 | 21.01 | 0.00 |
| **16.75** | 1.00 | 100.26 | **21.12** | 6.47 |
| **36.67** | 0.99 | 100.00 | **21.00** | 14.08 |
| **50.20** | 0.99 | 99.79 | **20.90** | 19.17 |
| 100.00 | 0.98 | 98.94 | 20.51 | 37.41 |
| 1000.00 | 0.86 | 87.98 | 15.71 | 281.30 |
| 10000.00 | 0.60 | 62.81 | 7.08 | 1241.66 |
| 50000.00 | 0.39 | 41.70 | 2.63 | 2297.79 |
| 100000.00 | 0.30 | 32.26 | 1.41 | 2465.13 |
| 300000.00 | 0.16 | 17.02 | 0.30 | 1566.45 |
| 500000.00 | 0.09 | 9.83 | 0.08 | 689.84 |
| 700000.00 | 0.05 | 5.07 | 0.02 | 193.68 |
| 900000.00 | 0.01 | 1.50 | 0.00 | 12.97 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 57B Data used for plotting SWCC for Kolfe sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.03 | 25.01 | 0.00 |
| **21.50** | 0.99 | 100.21 | **25.11** | 10.08 |
| **42.80** | 0.99 | 99.91 | **24.95** | 19.91 |
| **52.90** | 0.99 | 99.75 | **24.87** | 24.52 |
| 100.00 | 0.98 | 98.94 | 24.44 | 45.44 |
| 1000.00 | 0.86 | 87.98 | 18.87 | 341.71 |
| 10000.00 | 0.60 | 62.81 | 8.58 | 1508.34 |
| 50000.00 | 0.39 | 41.70 | 3.20 | 2791.30 |
| 100000.00 | 0.30 | 32.26 | 1.72 | 2994.58 |
| 300000.00 | 0.16 | 17.02 | 0.36 | 1902.89 |
| 500000.00 | 0.09 | 9.83 | 0.10 | 838.00 |
| 700000.00 | 0.05 | 5.07 | 0.02 | 235.28 |
| 900000.00 | 0.01 | 1.50 | 0.00 | 15.75 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 58A Data used for plotting SWCC for Addisu Gebeya sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.04 | 21.02 | 0.00 |
| **16.75** | 1.00 | 100.47 | **21.21** | 6.50 |
| **36.67** | 0.99 | 100.28 | **21.13** | 14.17 |
| **50.20** | 0.99 | 100.10 | **21.04** | 19.31 |
| 100.00 | 0.98 | 99.32 | 20.69 | 37.77 |
| 1000.00 | 0.86 | 88.62 | 16.13 | 289.16 |
| 10000.00 | 0.60 | 63.56 | 7.55 | 1326.19 |
| 50000.00 | 0.39 | 42.34 | 2.93 | 2557.78 |
| 100000.00 | 0.30 | 32.80 | 1.61 | 2811.39 |
| 300000.00 | 0.16 | 17.34 | 0.36 | 1891.65 |
| 500000.00 | 0.09 | 10.03 | 0.10 | 873.14 |
| 700000.00 | 0.05 | 5.17 | 0.02 | 259.14 |
| 900000.00 | 0.01 | 1.53 | 0.00 | 19.19 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 58B Data used for plotting SWCC for Addisu Gebeya sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.04 | 25.02 | 0.00 |
| **21.50** | 0.99 | 100.44 | **25.22** | 10.13 |
| **42.80** | 0.99 | 100.20 | **25.10** | 20.05 |
| **52.90** | 0.99 | 100.06 | **25.03** | 24.70 |
| 100.00 | 0.98 | 99.32 | 24.65 | 45.89 |
| 1000.00 | 0.86 | 88.62 | 19.35 | 351.26 |
| 10000.00 | 0.60 | 63.56 | 9.15 | 1611.02 |
| 50000.00 | 0.39 | 42.34 | 3.56 | 3107.12 |
| 100000.00 | 0.30 | 32.80 | 1.96 | 3415.20 |
| 300000.00 | 0.16 | 17.34 | 0.44 | 2297.93 |
| 500000.00 | 0.09 | 10.03 | 0.12 | 1060.66 |
| 700000.00 | 0.05 | 5.17 | 0.03 | 314.79 |
| 900000.00 | 0.01 | 1.53 | 0.00 | 23.31 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 59A Data used for plotting SWCC for Aweliya sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.01 | 21.00 | 0.00 |
| **16.75** | 1.00 | 99.89 | **20.95** | 6.41 |
| **36.67** | 0.99 | 99.51 | **20.77** | 13.91 |
| **50.20** | 0.99 | 99.24 | **20.64** | 18.91 |
| 100.00 | 0.98 | 98.24 | 20.17 | 36.74 |
| 1000.00 | 0.86 | 86.73 | 15.11 | 270.10 |
| 10000.00 | 0.60 | 61.35 | 6.55 | 1148.57 |
| 50000.00 | 0.39 | 40.46 | 2.35 | 2054.84 |
| 100000.00 | 0.30 | 31.22 | 1.24 | 2165.91 |
| 300000.00 | 0.16 | 16.40 | 0.25 | 1325.89 |
| 500000.00 | 0.09 | 9.46 | 0.07 | 567.87 |
| 700000.00 | 0.05 | 4.87 | 0.01 | 154.56 |
| 900000.00 | 0.01 | 1.44 | 0.00 | 9.80 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 59B Data used for plotting SWCC for Aweliya sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.01 | 25.01 | 0.00 |
| **21.50** | 0.99 | 99.80 | **24.89** | 9.98 |
| **42.80** | 0.99 | 99.39 | **24.67** | 19.66 |
| **52.90** | 0.99 | 99.18 | **24.56** | 24.17 |
| 100.00 | 0.98 | 98.24 | 24.05 | 44.63 |
| 1000.00 | 0.86 | 86.73 | 18.17 | 328.11 |
| 10000.00 | 0.60 | 61.35 | 7.94 | 1395.26 |
| 50000.00 | 0.39 | 40.46 | 2.86 | 2496.16 |
| 100000.00 | 0.30 | 31.22 | 1.51 | 2631.09 |
| 300000.00 | 0.16 | 16.40 | 0.31 | 1610.65 |
| 500000.00 | 0.09 | 9.46 | 0.08 | 689.84 |
| 700000.00 | 0.05 | 4.87 | 0.02 | 187.75 |
| 900000.00 | 0.01 | 1.44 | 0.00 | 11.91 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 60A Data used for plotting SWCC for Shegole sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.04 | 21.02 | 0.00 |
| **16.75** | 1.00 | 100.43 | **21.19** | 6.49 |
| **36.67** | 0.99 | 100.23 | **21.10** | 14.15 |
| **50.20** | 0.99 | 100.04 | **21.02** | 19.29 |
| 100.00 | 0.98 | 99.25 | 20.66 | 37.71 |
| 1000.00 | 0.86 | 88.50 | 16.07 | 287.99 |
| 10000.00 | 0.60 | 63.42 | 7.49 | 1314.67 |
| 50000.00 | 0.39 | 42.22 | 2.89 | 2523.50 |
| 100000.00 | 0.30 | 32.70 | 1.58 | 2766.24 |
| 300000.00 | 0.16 | 17.28 | 0.35 | 1849.84 |
| 500000.00 | 0.09 | 9.99 | 0.10 | 849.65 |
| 700000.00 | 0.05 | 5.16 | 0.02 | 250.73 |
| 900000.00 | 0.01 | 1.53 | 0.00 | 18.37 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 60B Data used for plotting SWCC for Shegole sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.04 | 25.02 | 0.00 |
| **21.50** | 0.99 | 100.39 | **25.20** | 10.12 |
| **42.80** | 0.99 | 100.15 | **25.08** | 20.03 |
| **52.90** | 0.99 | 100.00 | **25.00** | 24.67 |
| 100.00 | 0.98 | 99.25 | 24.61 | 45.81 |
| 1000.00 | 0.86 | 88.50 | 19.28 | 349.84 |
| 10000.00 | 0.60 | 63.42 | 9.07 | 1597.02 |
| 50000.00 | 0.39 | 42.22 | 3.51 | 3065.48 |
| 100000.00 | 0.30 | 32.70 | 1.92 | 3360.35 |
| 300000.00 | 0.16 | 17.28 | 0.43 | 2247.14 |
| 500000.00 | 0.09 | 9.99 | 0.12 | 1032.13 |
| 700000.00 | 0.05 | 5.16 | 0.02 | 304.58 |
| 900000.00 | 0.01 | 1.53 | 0.00 | 22.32 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 61A Data used for plotting SWCC for Bole sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.16 | 12.76 | 0.00 |
| **23.10** | 0.99 | 102.00 | **12.96** | 5.31 |
| **32.90** | 0.99 | 102.07 | **12.96** | 7.57 |
| **48.60** | 0.99 | 102.07 | **12.96** | 11.19 |
| 100.00 | 0.98 | 101.68 | 12.92 | 22.94 |
| 1000.00 | 0.86 | 92.31 | 11.90 | 210.79 |
| 10000.00 | 0.60 | 67.73 | 9.13 | 1606.94 |
| 50000.00 | 0.39 | 45.92 | 6.52 | 5715.36 |
| 100000.00 | 0.30 | 35.85 | 5.26 | 9200.41 |
| 300000.00 | 0.16 | 19.17 | 3.04 | 15950.94 |
| 500000.00 | 0.09 | 11.15 | 1.89 | 16529.39 |
| 700000.00 | 0.05 | 5.77 | 1.06 | 12998.88 |
| 900000.00 | 0.01 | 1.71 | 0.37 | 5763.38 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 61B Data used for plotting SWCC for Bole sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.16 | 13.98 | 0.00 |
| **14.50** | 1.00 | 101.85 | **14.18** | 3.66 |
| **38.80** | 0.99 | 102.09 | **14.20** | 9.82 |
| **52.00** | 0.99 | 102.06 | **14.20** | 13.16 |
| 100.00 | 0.98 | 101.68 | 14.16 | 25.22 |
| 1000.00 | 0.86 | 92.31 | 13.05 | 231.76 |
| 10000.00 | 0.60 | 67.73 | 10.02 | 1766.80 |
| 50000.00 | 0.39 | 45.92 | 7.16 | 6283.95 |
| 100000.00 | 0.30 | 35.85 | 5.78 | 10115.73 |
| 300000.00 | 0.16 | 19.17 | 3.35 | 17537.84 |
| 500000.00 | 0.09 | 11.15 | 2.08 | 18173.84 |
| 700000.00 | 0.05 | 5.77 | 1.17 | 14292.09 |
| 900000.00 | 0.01 | 1.71 | 0.40 | 6336.75 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 62A Data used for plotting SWCC for CMC sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.19 | 12.74 | 0.00 |
| **23.10** | 0.99 | 102.33 | **12.73** | 5.22 |
| **32.90** | 0.99 | 102.42 | **12.73** | 7.43 |
| **48.60** | 0.99 | 102.45 | **12.73** | 10.98 |
| 100.00 | 0.98 | 102.12 | 12.73 | 22.59 |
| 1000.00 | 0.86 | 92.96 | 12.77 | 226.66 |
| 10000.00 | 0.60 | 68.43 | 12.90 | 2290.30 |
| 50000.00 | 0.39 | 46.52 | 13.06 | 11602.82 |
| 100000.00 | 0.30 | 36.35 | 13.17 | 23400.97 |
| 300000.00 | 0.16 | 19.48 | 13.44 | 71708.13 |
| 500000.00 | 0.09 | 11.34 | 13.68 | 121734.34 |
| 700000.00 | 0.05 | 5.88 | 13.98 | 174282.25 |
| 900000.00 | 0.01 | 1.74 | 14.55 | 233525.93 |
| 1000000.00 | 0.00 | 0.00 | 35.72 | 719088.10 |

Table A- 62B Data used for plotting SWCC for CMC sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.19 | 13.96 | 0.00 |
| **14.50** | 1.00 | 102.14 | **13.95** | 3.60 |
| **38.80** | 0.99 | 102.45 | **13.95** | 9.64 |
| **52.00** | 0.99 | 102.45 | **13.95** | 12.92 |
| 100.00 | 0.98 | 102.12 | 13.95 | 24.84 |
| 1000.00 | 0.86 | 92.96 | 13.99 | 249.20 |
| 10000.00 | 0.60 | 68.43 | 14.13 | 2518.15 |
| 50000.00 | 0.39 | 46.52 | 14.31 | 12757.13 |
| 100000.00 | 0.30 | 36.35 | 14.43 | 25729.04 |
| 300000.00 | 0.16 | 19.48 | 14.72 | 78842.10 |
| 500000.00 | 0.09 | 11.34 | 14.99 | 133845.22 |
| 700000.00 | 0.05 | 5.88 | 15.31 | 191620.92 |
| 900000.00 | 0.01 | 1.74 | 15.92 | 256758.53 |
| 1000000.00 | 0.00 | 0.00 | 38.33 | 790627.40 |

Table A- 63A Data used for plotting SWCC for Emperial Site sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.17 | 12.75 | 0.00 |
| **23.10** | 0.99 | 102.12 | **12.86** | 5.27 |
| **32.90** | 0.99 | 102.20 | **12.87** | 7.52 |
| **48.60** | 0.99 | 102.21 | **12.87** | 11.10 |
| 100.00 | 0.98 | 101.84 | 12.85 | 22.80 |
| 1000.00 | 0.86 | 92.55 | 12.30 | 217.98 |
| 10000.00 | 0.60 | 67.99 | 10.67 | 1884.40 |
| 50000.00 | 0.39 | 46.14 | 8.92 | 7845.94 |
| 100000.00 | 0.30 | 36.04 | 7.95 | 13962.91 |
| 300000.00 | 0.16 | 19.29 | 5.93 | 31183.88 |
| 500000.00 | 0.09 | 11.22 | 4.60 | 40238.94 |
| 700000.00 | 0.05 | 5.81 | 3.38 | 41291.04 |
| 900000.00 | 0.01 | 1.72 | 1.90 | 29915.53 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 63B Data used for plotting SWCC for Emperial Hotel Site sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.17 | 13.97 | 0.00 |
| **14.50** | 1.00 | 101.96 | **14.08** | 3.64 |
| **38.80** | 0.99 | 102.22 | **14.10** | 9.75 |
| **52.00** | 0.99 | 102.20 | **14.10** | 13.06 |
| 100.00 | 0.98 | 101.84 | 14.08 | 25.07 |
| 1000.00 | 0.86 | 92.55 | 13.48 | 239.67 |
| 10000.00 | 0.60 | 67.99 | 11.71 | 2071.87 |
| 50000.00 | 0.39 | 46.14 | 9.79 | 8626.50 |
| 100000.00 | 0.30 | 36.04 | 8.73 | 15352.03 |
| 300000.00 | 0.16 | 19.29 | 6.52 | 34286.24 |
| 500000.00 | 0.09 | 11.22 | 5.06 | 44242.16 |
| 700000.00 | 0.05 | 5.81 | 3.71 | 45398.93 |
| 900000.00 | 0.01 | 1.72 | 2.09 | 32891.71 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 64A Data used for plotting SWCC for Hayahulet Site sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.10 | 12.76 | 0.00 |
| **23.10** | 0.99 | 101.36 | **12.99** | 5.33 |
| **32.90** | 0.99 | 101.36 | **12.99** | 7.59 |
| **48.60** | 0.99 | 101.29 | **12.97** | 11.20 |
| 100.00 | 0.98 | 100.75 | 12.87 | 22.86 |
| 1000.00 | 0.86 | 90.92 | 11.13 | 196.70 |
| 10000.00 | 0.60 | 66.19 | 7.05 | 1236.03 |
| 50000.00 | 0.39 | 44.60 | 3.97 | 3467.43 |
| 100000.00 | 0.30 | 34.72 | 2.75 | 4806.89 |
| 300000.00 | 0.16 | 18.49 | 1.10 | 5734.98 |
| 500000.00 | 0.09 | 10.73 | 0.49 | 4309.96 |
| 700000.00 | 0.05 | 5.55 | 0.19 | 2298.74 |
| 900000.00 | 0.01 | 1.65 | 0.03 | 498.75 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table A- 64B Data used for plotting SWCC for Hayahulet Site sample

| h(kPa) | C(h) | S(%) | Φbp(°) | τus (kPa) |
|---|---|---|---|---|
| 0.01 | 1.00 | 100.10 | 13.98 | 0.00 |
| **14.50** | 1.00 | 101.28 | **14.21** | 3.67 |
| **38.80** | 0.99 | 101.34 | **14.22** | 9.84 |
| **52.00** | 0.99 | 101.26 | **14.21** | 13.17 |
| 100.00 | 0.98 | 100.75 | 14.11 | 25.13 |
| 1000.00 | 0.86 | 90.92 | 12.20 | 216.27 |
| 10000.00 | 0.60 | 66.19 | 7.74 | 1359.00 |
| 50000.00 | 0.39 | 44.60 | 4.36 | 3812.39 |
| 100000.00 | 0.30 | 34.72 | 3.03 | 5285.11 |
| 300000.00 | 0.16 | 18.49 | 1.20 | 6305.53 |
| 500000.00 | 0.09 | 10.73 | 0.54 | 4738.74 |
| 700000.00 | 0.05 | 5.55 | 0.21 | 2527.43 |
| 900000.00 | 0.01 | 1.65 | 0.03 | 548.37 |
| 1000000.00 | 0.00 | 0.00 | 0.00 | 0.00 |