SOIL-WATER CHARACTERISTIC CURVE (SWCC)
FOR FMC KAOLIN

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ABSTRACT

As the world's population has grown and become more urban and affluent, waste production has risen tenfold. Discarded materials are collected, some are recycled or composted, and most are landfilled or incinerated. But in spite of the aggressive economic development, the waste management is relatively poor. This will lead to the contamination of soil at the landfill which raised environmental concern and initiated the involvement of geotechnical engineers in environmental matters. Geoenvironmental engineering covers the aspect of contaminated site remediation and the prevention of future contaminated sites. Clays are one of the alternatives used in the management of wastes disposal at landfills. Clays act as environmental barriers around waste disposal site where they are used as liners and capping materials for landfills sites. Highly plastic clays are used as barriers in landfills and nuclear waste repository. For each application the engineering properties of the clays must be carefully designed to obtain the desired result. Studies concerning changes in the water content as affected by a change in the soil suction are extremely crucial for a long-term assessment of the engineering behaviour of clays. Thus, this thesis experimentally investigated the changes in the water content of initially slurried clay during the drying process. The kaolinite clay which is FMC kaolin was use. The osmotic and vapour equilibrium technique were used in this study to establish soil-water characteristics curve (SWCC) which is subjected to drying process. The graphs of water content over varying suctions and water content over elapsed time are establish for each technique and then combine to show the curve of the drying process ranging from low suction to high suction value. As conclusion, FMC kaolin is suitable to be used as a admixture because of its non-swelling properties where it can absorb water and undergo little volume changes only.

ABSTRAK

Seiring dengan peningkatan penduduk dunia dan berkembang menjadi lebih maju dan mewah, pengeluaran sisa telah meningkat sepuluh kali ganda. Bahan-bahan terbuang yang dikumpul, ada yang dikitar semula atau di kompos, dan kebanyakan di kumpulkan di tapak pelupusan atau dibakar. Pengurusan sisa buangan tidak terurus tidak seiring dengan pembangunan ekonomi yang agresif. Ini akan membawa kepada pencemaran tanah di tapak pelupusan yang menimbulkan masalah pencemaran alam sekitar dan melibatkan jurutera geoteknik dalam hal-hal alam sekitar. Kejuruteraan geoenvironmental meliputi aspek tapak pemulihan yang tercemar dan pencegahan tapak tercemar pada masa akan datang. Tanah liat adalah salah satu alternatif yang digunakan dalam pengurusan sisa pelupusan di tapak pelupusan. Tanah liat bertindak sebagai halangan alam sekitar di sekitar tapak pelupusan sampah di mana ia digunakan sebagai alas dan bahan-bahan untuk menutup tapak pelupusan tapak. Tanah liat yang mempunyai sifat sangat plastik digunakan sebagai halangan di tapak pelupusan dan penyimpanan sisa nuklear. Bagi setiap kegunaan sifat kejuruteraan tanah liat perlu disiasat dengan teliti untuk mendapatkan keputusan yang dikehendaki. Kajian mengenai perubahan dalam kandungan air yang terjejas oleh perubahan dalam sedutan tanah amat penting bagi penilaian jangka panjang karakter kejuruteraan tanah liat. Oleh itu,tesis ini menyiasat dengan melakukan eksperimen keatas perubahan dalam kandungan air tanah liat mulanya berair semasa proses pengeringan. Tanah liat kaolinit yang digunakan adalah FMC kaolin. Osmotik dan keseimbangan wap teknik telah digunakan dalam kajian ini untuk mewujudkan ciri-ciri tanah-air lengkung (SWCC) dibawah proses pengeringan. Graf kandungan air versus sedutan yang berbeza-beza dan kandungan air versus masa diambil di plot bagi setiap teknik dan kemudian digabungkan untuk menunjukkan lengkung proses pengeringan antara sedutan rendah kepada nilai sedutan tinggi. Kesimpulannya, FMC kaolin sesuai digunakan sebagai bahan tambahan kerana sifat-sifat yang tidak kembang di mana ia boleh menyerap air dan hanya berubah sedikit sahaja dalam isipadu.

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^{o}	Angle
^{o}C	Temperature
π	Osmotic suction
u_{a}	Pore-air pressure
u_{w}	Pore-water pressure
$(\sigma - u_{a})$	Net normal stress
$(u_{a} - u_{w})$	Matric suction
h_{o}	Osmotic pressure
Ψ	Total suction
θ	Volumetric water content
s	Suction
w	Water content
ρ	Density
V	Volume

LIST OF ABBREVIATIONS

SWCC	Soil-Water Characteristic Curve
AEV	Air Entry Value
HAEV	High Air Entry Value
RWC	Residual Water Content
REV	Representative Elementary Volume
VET	Vapour Equilibrium Technique
PEG	Polyethleneglycol
EGME	Ethylene Glycol Monoethyl Ether
LOI	Loss on Ignition
AASHTO	American Association of State Highway and Transportation Officials
BS	British Standard

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

According to the Environmental Protection Agency (EPA), the average person dumps almost 4.5 pounds of waste into landfills every single day. With the population skyrocketing across the country, these landfills will only become more of a public issue as time goes on. Despite the arguments over landfills in general, there are no arguments over the assertion that there are many things that contribute to the environmental problem of landfills. The environmental problems caused by landfills are numerous. While there are many problems with landfills, the negative effects are most commonly placed into two distinct categories: atmospheric effects and hydrological effects. (Jared, 2014). Landfills also create a toxic soup of industrial and home-cleaning chemicals. People throw away everything from industrial solvents to household cleaners in landfills, and these chemicals accumulate and mix over time. The onset of such problems raised environmental concern and initiated the involvement of geotechnical engineers in environmental matters. Geoenvironmental engineering covers the aspect of contaminated site remediation and the prevention of future contaminated sites.

One of the alternatives used to solve the problems is by using the natural sources that are clays. Clays act as environmental barriers around waste disposal site where they are used as liners and capping materials for landfills sites. The clay liners act as barriers to water and containment flow in landfills and other waste containment facilities. Highly plastic clays are used as barriers in landfills and nuclear waste repository (Daniel, 2003; Pusch, 2005). Furthermore, clays also used for geo-environmental application in remediation, treatment and control of waste (Sharma & Reddy, 2004).

Clays are used for barriers because its behaviour related to the volume change (i.e. the shrinkage and swelling processes) due to changes in the water content (Delage and Romero, 2008; Abuel-Naga and Bouazza, 2010). The drying and wetting behaviour (i.e. soil-water characteristic curves, SWCCs) of clays have been extensively studied in the past (Croney and Coleman, 1954; Fleureau *et al*., 1993; Barbour, 1998; Delage *et al*., 1998; Marcial *et al*., 2002). SWCC can be used to estimate the soil properties such as volume change characteristic, permeability and shear strength functions (Fredlund, 2006).

In some cases, naturally occurring fine grained soils containing kaolinite serve as the undisturbed clayey barriers (Yang and Barbour, 1992). Additionally, in an attempt to develop low cost technologies, locally available kaolinite-rich soils are preferred as the mineral liners. In order to identify the engineering behavior of the soil, a study focus on FMC Kaolin clay need to be done to study its drying path of soil-water characteristic curve (SWCC). The theory and components of SWCC will be discussed in detail in chapter 2.

1.2 PROBLEM STATEMENT

To understand and to evaluate or predict soil behaviour, one needs to have information on the properties of the soil under consideration. This information can be obtained by soil-water characteristic curve (SWCC) which is subjected to drying process. The suction-water content soil-water characteristic curves (SWCCs) provide useful information for predicting the engineering behaviour of soils such as shear strength, volume change behaviour, permeability and compressibility. Thus it is very important to establish the suction-water content SWCC of soils. The is lack of information published on locally available commercialized clay in Malaysia, thus this study is hope to establish the suction-water content for KMC kaolin.

1.3 OBJECTIVE

There are several objectives to be accomplished through this study.

1. To determine the physical properties of FMC kaolin.
2. To establish the drying suction-water content (SWCC) for FMC kaolin.

1.4 SCOPE OF STUDY

To reach the objectives of this project, several analysis and testing were carried out in Soil and Geotechnical Laboratory at Universiti Malaysia Pahang. Variables of this project are a water content of the FMC Kaolin and soil suction . The initial state of soil specimens are slurry at initial water content of 1.2 times the liquid limit. Drying test will be conducted for suction applied of 0.1 – 120 MPa using the osmotic and the vapour equilibrium techniques.

1.5 THESIS LAYOUT

This thesis consists of five consecutive chapters. Chapter 2 presents the literature review conducted that are related to this research study. This chapter includes kaolinite clay minerology, clay-water interaction, soil suction and soil water characteristic curve(SWCC).

Chapter 3 is methodology. This chapter explains the methodologies adopted in this study. This chapter covers all steps and procedures required for the sample preparation, determination of bentonite clay properties (specific gravity, initial water content, Atterberg limit, particle size distribution and soil mineral properties), and determination drying path by osmotic test and vapour equilibrium test.

Chapter 4 consists of results and discussion obtained from the study. This chapter includes the outcome obtained through the tests done in the determination of kaolinite properties. It also include the results obtained from the drying process of the kaolinite clay which are then will be used to discuss the behavior of suction in kaolinite clay, and to develop the SWCC.

Chapter 5 is the conclusion and recommendations. This chapter summarizes the whole purpose of this study, the significance and important of this study for future references.

CHAPTER 2

LITERATURE REVIEW

2.1 CLAY MINERALS

Clay minerals feature prominently in the clay-sized fractions of most soils. They are secondary minerals obtained from chemical weathering of primary minerals in metamorphic and sedimentary rocks (Raymond, Nakano *et al*., 2012) The processes involved include incongruent reactions such as formation of new mineral structures from dissolved products, which will change the molar ratios of the chemical elements in solution. The molar ratios will be different from those in the source rocks. Often, clays exhibit a lamellar structure as a consequence of the crystalline arrangement formed by the man components of clays which are silicon and aliminium oxides.

These structures displayed by these materials, tetrahedral for silicon oxide and octahedral for aluminium oxide combine to form a unique structural arrangement in which sheets of tetrahedral and octahedral overlap each other, leading to structural changes such as 2:1 (one octahedral sheet between two octahedral sheets) and 1:1 (one tetrahedral sheet to one octahedral sheet) that characterize the various clay minerals (Valenzuela-Díaz et al., 1992). Kaolin and bentonite clays, the most studied clays presenting structure 1:1 and 2:1 respectively.

The influential role of clay minerals in soil properties and soil properties behaviour is derived from their particle size and shape, their large specific surface area in contrast to the soil particles of larger dimensions, and their physicochemical activities. The types and proportions of minerals present in clay significantly influence its index properties

2.2 KAOLIN

The kaolin clay, also known as “china clay” is chemically a hydrous aluminium silicate characterized as very fine powder, chemical inertness and lamellar structure (1:1) formed under acidic conditions through weathering or hydrothermal changes of feldspar. It can form independent weathered kaolin deposits, kaolinite clays or may be a compound of kaolinite sandstones and oolitic ironstones.

The most significant kaolin deposits were formed through intensive weathering of rocks rich in feldspar. Millions years ago, original material was decomposed by weathering, giving rise to kaolin and silica combined with higher or lower of admixtures. Mechanical erosion formed the rock under the tropical climate of that era and it increased temperatures, chemical corrosion occurred under the activity of water saturated with carbon dioxide and humic acids which eluted from water (Bernard and Rost,1992; Slivka, 2002).

Kaolin serves an important function in the cement industry as highly calcinated, pulverized kaolin adds compressive strength, flexural strength and water permeability to cement. In general 5-15% activated kaolin mixed with cement creates a superiorly strong mortar when hardened. Water permeability is useful in prolonging the durability of concrete and reduces weakening as a whole; calcined kaolin adds flexibility, which is often preferred to the usually brittle finished product. High performance concrete (cement with kaolin additives) can be modified to meet a variety of applications. In particular its shrinkage, strength when compressed, and water permeability makes high performance concrete useful in bridge building.

2.2.1 Kaolin Structure

Kaolin is a plastic raw material, particularly consist of the ckay mineral kaolinite. The chemical formula is $Al_2O_3.2SiO_2.2H_2O$ (39.5% Al_2O_3, 46.5% SiO_2, 14.0% H_2O**).** In systemic mineralogy, kaolinite ranks among phyllosilicates, which are stratified clay minerals formed by a net of tetrahedral and octahedral layers. Phyllosilicates are classified into the main groups according to the type of the layers, interlayer content, charge of the layers and chemical formulas. Group of kaolinites includes di-octahedral minerals (1:1) with two layers, one silica (SiO_4) tetrahedral layer and one aluminium ($Al_2(OH)_4$) octahedral layer as shown in figure 2.1. The layers are bonded together by sharing oxygen anion between Al and Si. Together, these two layers are called platelets (Pauk et al., 1962; Stejskal, 1971; Bailey, 1980; Duda et al., 1990).

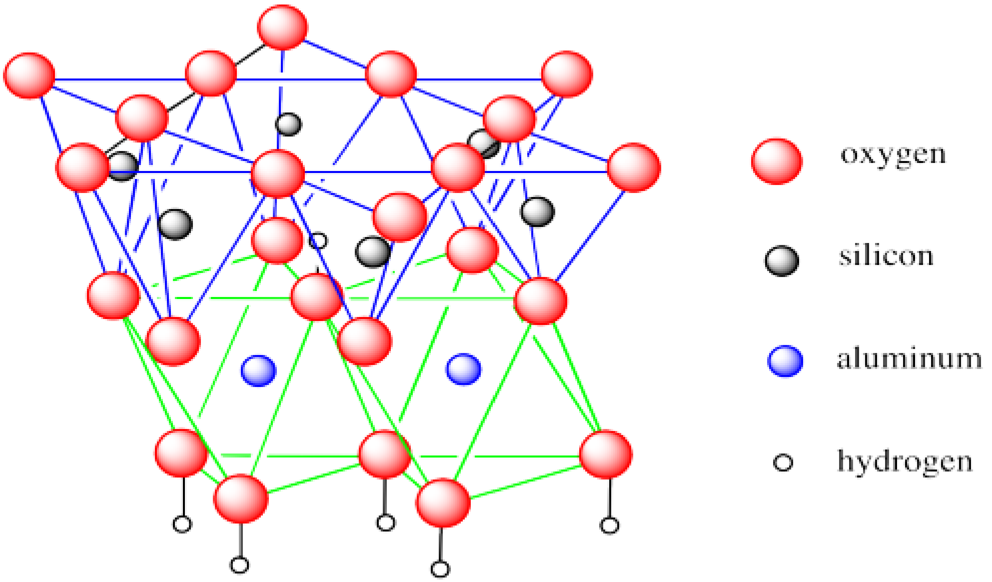

Figure 2.1 : Diagram of kaolinite layer structure (after Grim, 1968)

2.2.2 Clay-Water Interaction

A net negative charge can be found on the surfaces of the clay particles. This is due to the isomorphous substitution and of a break in continuity of the structure at its edges. Larger specific surfaces can produce larger negative charges. Apart of that, some positively charged sites also occur at the edges of the particles. The negative charge is balanced by exchangeable cations like Ca^{2+}, Mg^{2+}, and K^{+} surrounding the particles being held by electrostatic attraction in dry clays. These cations and a few anions float around the clay particles when water is added to clay. This configuration is referred to as a diffuse double layer. The cation concentration decreases with the distance from the surface of the particle. Water molecules are polar. Hydrogen atoms are not axisymmetric around an oxygen atom but instead they occur at a bonded angle of 105^{O}.

As a result, a water molecule has a positive charge at one side and a negative charge at the other side. It is known as a dipole. The negatively charged surface of the clay particles and the cations in the double layer attracted the dipolar water. Whereas, the soil particles are attracted the cations. Hydrogen bonding is a third mechanism by which water is attracted to clay particles where hydrogen atoms in the water molecules are shared with oxygen atoms on the surface of the clay. Some partially hydrated cations in the pore water are also attracted to the surface of clay particles. These cations attract dipolar water molecules. All these possible mechanics of attraction of water to clay are shown in Figure 2.2.

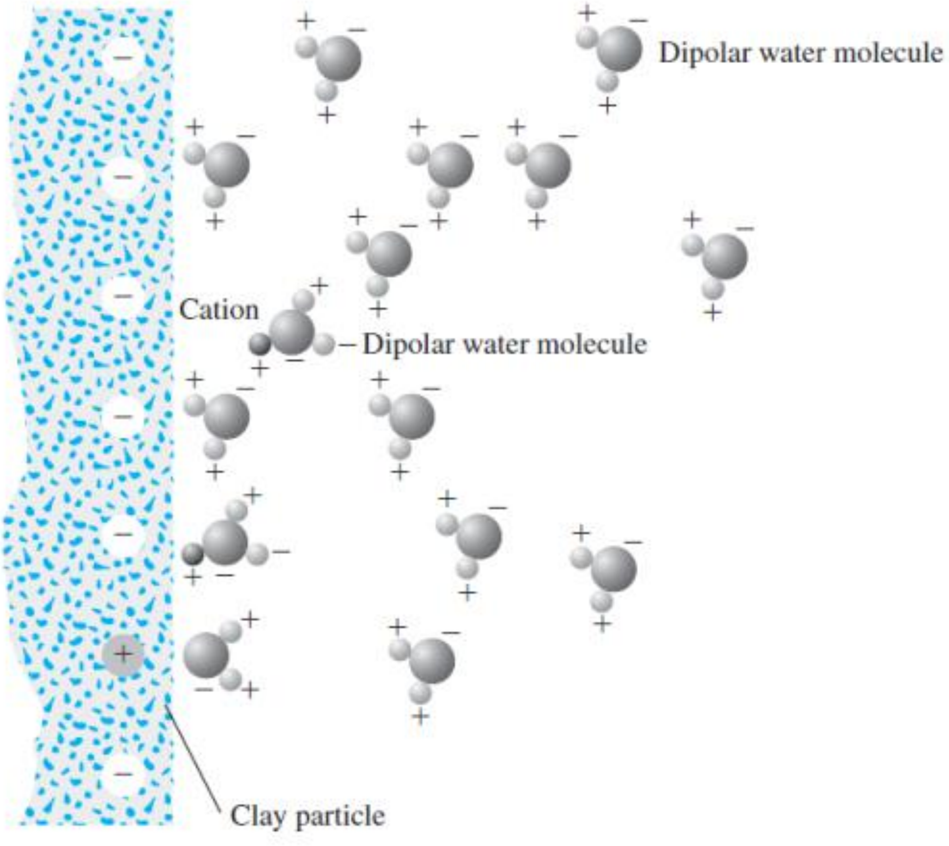

Figure 2.2 : Attraction of dipolar molecules in diffuse double layer (after Das, 2010)

The force of attraction between water and clay decreases with distance from the surface of the particles. Double-layer water occurs when all the water held to clay particles by force of attraction. The innermost layer of double-layer water, which is held very strongly by clay, is known as adsorbed water. This water is more viscous than free water is.

The plastic properties of the clay soils are due to the orientation of water around the clay particles. It needs to be well recognized that the presence of clay minerals in a soil aggregate has a great influence on the engineering properties of the soil. The present of moisture in clay influenced the engineering behavior of a soil as the percentage of clay mineral content increases. For all practical purposes, when the clay content is about 50% or more, the sand and silt particles float in clay.

2.3 SOIL SUCTION

The theoretical concept of soil suction was developed in soil physics regarding the soil water-plant system in the early 1900's (Buckingham, 1907; Gardner and Widtsoe, 1921). In soil physics, soil suction is commonly referred to as the free energy state of soil water (Edlefsen and Anderson, 1943). It can be measured in terms of the partial vapor pressure of the soil water (Richards, 1965) and represents the thermodynamic potential pore water relative to free water, where the free water is defined as water with no dissolved solutes. The use of soil suction in explaining the mechanical behavior of unsaturated soils in relation to engineering problems was introduced by Croney and Coleman (1948).

2.3.1 Osmotic Suction

Osmotic suction, π, represents suction that originates from dissolved solutes in the pore water which reduce the energy state of the water in soil. It is the equivalent suction derived from the measurement of the partial pressure of the water vapor in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapor in equilibrium with free pure water.

Figure 2.3 illustrates the nature of osmotic suction by showing a chamber of water divided by a semi-permeable membrane. On one side of the membrane is pure water, and on the other side is a salt solution. The semipermeable membrane will allow water molecules to pass through it but not salt molecules. The concentration of the solution causes an attraction to water molecules and hence, tending to force the pure water to flow into the salt solution through the semipermeable membrane. The pressure that the salt solution can exert on the pore water depends on the concentration of the salt in the solution. This pressure is called the osmotic pressure represented by h_o in terms of osmotic pressure head in Figure 2.3. This pressure is the osmotic suction of the soil.

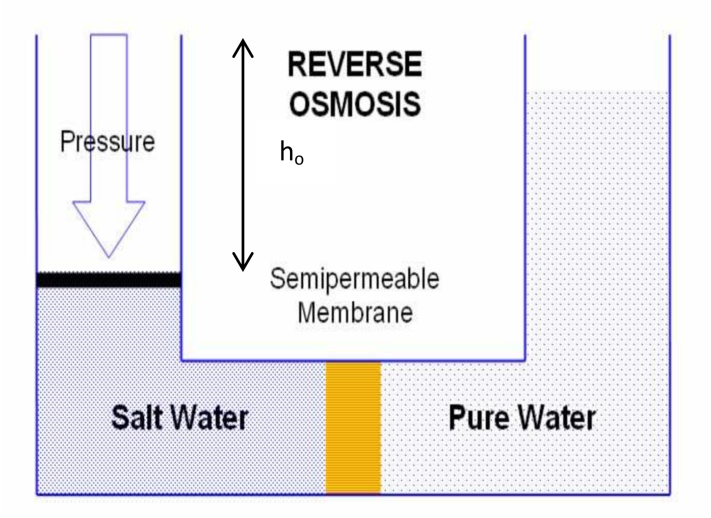

Figure 2.3 : Osmotic Pressure Across a Semipermeable Membrane (after Nelson and Miller, 1996)

Miller (1996) and Miller and Nelson (2006) showed that osmotic suction, π, is a valid, independent, stress state variable in soils. Thus, the complete rigorous definition of stress state of an unsaturated soil thus requires three independent variables which are net normal stress, $(\sigma - u_a)$, matric suction, $(u_a - u_w)$, and osmotic suction, π. Appropriate constitutive parameters must be used to associate changes in these stress state variables with changes in soil volume. Generally in geotechnical engineering, changes in osmotic suction are negligible.

2.3.2 Matric Suction

Matric suction is a variable that quantifies the soil water potential with respect to the potential at the ambient atmospheric condition. By definition, matric suction is the pressure difference between the pore air pressure u_a and the pore-water pressure u_w, i.e., $(u_a - u_w)$ (Fredlund and Morgenstern, 1977). Therefore, the value of matric suction is the soil water pressure deficit with respect to air pressure, or the soil water potential deficit with respect to soil water potential at the ambient air pressure. For example, a value of 1 Pa of matric suction indicates that the soil water pressure is 1 Pa below the ambient air pressure, or, 1 J /m^3 of pressure potential below the water pressure potential at the ambient air pressure.

It is important to recognize that matric suction represents the energy (J) per unit volume of soil water (m^3), not per unit volume of unsaturated soil, as it is defined at the pore-scale level with respect to the constituents of air and water. Thus, it may be reasoned that matric suction cannot fully define the specific energy or pore water pressure with respect to the multiphase air-water-solid of the reprsentative elementary volume (REV) previously conceptualized for unsaturated soil, where stress variables are accounted for following classical mechanics. For example, to compute the pressure potential or energy per unit soil volume (i.e., on the scale of the air-water-solid REV), matric suction must be multiplied by volumetric water content θ (defined as the volume of water over the REV volume), i.e., $(u_a – u_w)\ \theta$. For soils with matric suction of 1 Pa, the total energy stored in 1 m^3 of soil-water is the same, namely, 1 J. However, the total energy stored in 1 m^3 of unsaturated soil greatly depends on water content, which varies from soil to soil (Lu and Likos, 2006).

2.3.3 Total Suction

The soil suction as quantified in terms of the relative humadity is commonly called “total suction”. The total suction of soil is divided into two components, namely, matric and osmotic suction. Equation 2.1 shows,

$$\Psi = (u_a - u_w) + \pi \qquad \text{(Eq. 2.1)}$$

where,

$(u_a - u_w)$ = matric suction
u_a = pore-air pressure
u_w = pore-water pressure
π = osmotic suction

In terms of their effect on the behavior of soil, they must be considered independently (Miller and Nelson, 1993). Figure 2.5 shows experimental data illustrating that the matric suction plus the osmotic suction are about equal to the total suction of the soil, as presented by Krahn and Fredlund (1972). The presented data are for gracial till specimens compacted under modified AASHTO conditions at various initial water contents. Each component of soil suction and the total suction were measured independently.

Figure 2.4 indicates that the initial water content of compacted soils is directly related to the matric suction component. The osmotic suction remains fairly consistent with an average value of approximately 300 kPa in the range of water content from 11 to 17%. Consequently, the change in the total suction is quite representative of the change in matric suction within the range of water contents encountered in most practical geotechnical engineering problems.

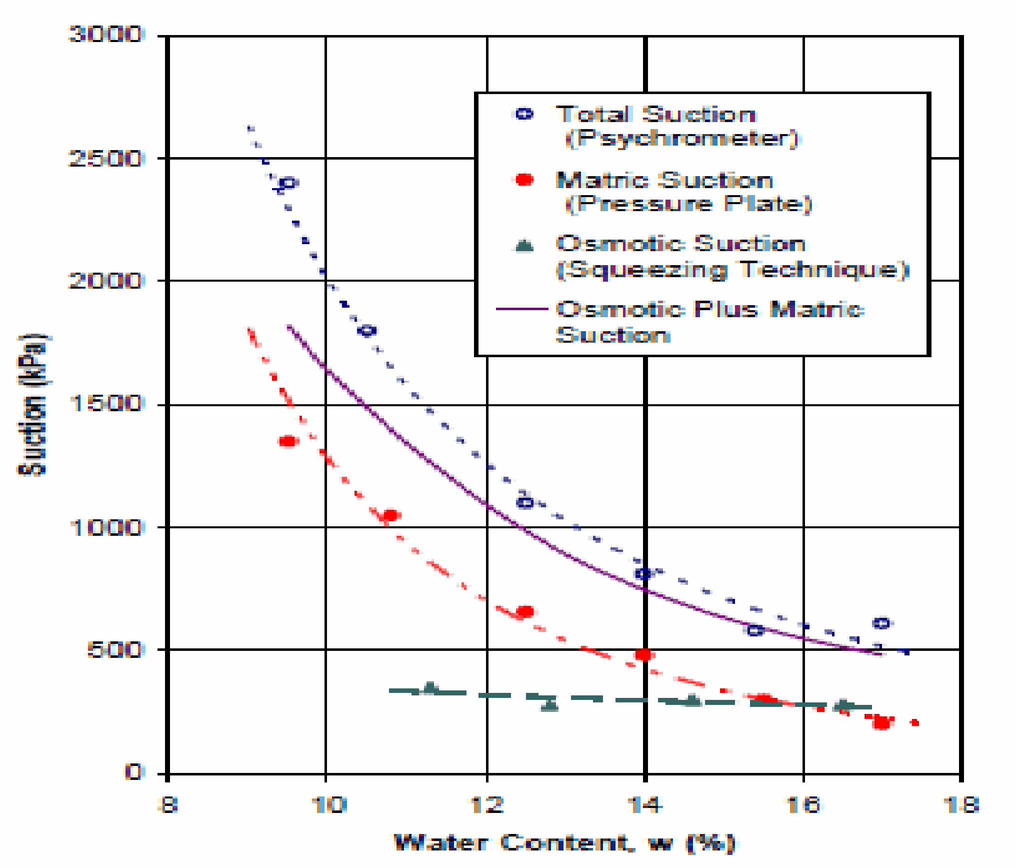

Figure 2.4 : Total, Matric, and Osmotic Suctions for Glacial Till

(after Krahn and Fredlund, 1972)

2.4 SOIL WATER CHARACTERISTIC CURVE (SWCC)

The Soil Water Characteristic Curve (SWCC) also known as water retention curve is one of the fundamental properties of unsaturated soils. It plays the major role in describing the nature, the mechanical and hydraulic behaviour of unsaturated soils. The soil-water characteristic curves are important pieces of information that reflect that changing water content processes, and are useful in analyses of water uptake, drainage, and water flow in engineering projects. Originally developed by soil and agricultural science, SWCC has gained popularity within the geotechnical engineering community.

SWCC is a graphical representation of water content versus soil suction relationship as shown in Figure 2.5 under condition where the normal stress is zero or a small value. Main components of SWCC curve are the air entry value (AEV), residual water content (RWC) and the slope of SWCC curve. The AEV is defined as the soil suction at which air first enters the largest pores of the soil and desaturation starts. RWC is the water content beyond which further increase in pore water pressure causes little variation in water content. The slope of soil-water characteristic curve represents the slope of line connecting AEV and RWC. The part of the curve before the AEV value represents the stage where all soil pores are filled with water and hence represents saturated volumetric water content (Fredlund and Rahardjo, 1993).