# Temperature Effect on the Soil Water Retention Characteristic

By

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ABSTRACT

The importance of unsaturated soil behavior stems from the fact that a vast majority of infrastructures are founded on unsaturated soils. Research has recently been concentrated on unsaturated soil properties. In the evaluation of unsaturated soils, researchers agree that soil water retention characterized by the soil water characteristic curve (SWCC) is among the most important factors when assessing fluid flow, volume change and shear strength for these soils.

The temperature influence on soil moisture flow is a major concern in the design of important engineering systems such as barriers in underground repositories for radioactive waste disposal, ground-source heat pump (GSHP) systems, evapotranspirative (ET) covers and pavement systems.. Accurate modeling of the temperature effect on the SWCC may lead to reduction in design costs, simpler constructability, and hence, more sustainable structures.

. The study made use of two possible approaches to assess the temperature effect on the SWCC.  In the first approach, soils were sorted from a large soil database into families of similar properties but located on sites with different MAAT. The SWCCs were plotted for each family of soils. Most families of soils showed a clear trend indicating the influence of temperature on the soil water retention curve at low degrees of saturation.. The second approach made use of statistical analysis. It was demonstrated that the suction increases as the MAAT decreases.  The statistical analysis showed that even though the plasticity index proved to have the greatest influence on suction, the mean annual air temperature effect proved not to be negligible. In both approaches, a strong relationship between temperature, suction and soil properties was observed. Finally, a comparison of the model based on the mean annual air temperature environmental factor was compared to another model that makes use of the Thornthwaite Moisture Index (TMI) to estimate the environmental effects on the suction of unsaturated soils. Results showed that the MAAT can be a better indicator when compared to the TMI found but the results were inconclusive due to the lack of TMI data available.

DEDICATION

To my husband and kids

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# Chapter 1

# OVERVIEW

There are a variety of important geotechnical problems where temperature variation occurs during water flow in unsaturated soils. Examples of where this thermo-hydraulic phenomenon is important include: 1) Thermal behavior of ground as a source of geothermal energy; 2) Analysis of barriers for nuclear waste storage; 3) Water balance of evapotranspirative (ET) covers for municipal solid waste containment; 4) Assessment of vapor barriers for building slabs and subsurface walls; 5) Heat transfer/dissipation from buried electrical cables, underground tanks and pipelines; 6) Heat applied directly to the soil to clean up degraded areas; 7) Vapor migration calculations at contaminated soil and groundwater sites, and remediation performance estimates; and 8) Coupled thermal-moisture movements in pavement systems. During these thermo-hydraulic processes, temperature variation near the potential site can give rise to both water vaporization in the high temperature zone, and condensation in the low temperature zone. Other typical examples involving temperature effects on unsaturated flow include, steam flushing for removal of non-aqueous phase fluids from the subsurface (She and Sleep 1998). Understanding and modeling this process is critical for assessing the engineering design for each application.

It has been agreed upon that hydraulic properties of porous media such as hydraulic conductivity and water retention are temperature-dependent. Not taking this properties effect into account can cause an error in the design process (Philip and de Vries 1957).

There has been a substantial amount of effort in understanding the temperature effect on the hydraulic conductivity by using the viscosity theory (Hopmans and Dane 1986). However, there has been a minimal effort in explaining the temperature effect on the soil water characteristic curve. Most of the previous experimental and theoretical efforts have been restricted to clay soil or bentonite. Moreover, a study that considers a wide variety of soils or a wide range of temperatures could not be found (Jacinto et al. 2007).

## Thesis objectives

In this study, soil properties and information of a wide range of soils were collected from a large database available from the National Resources Conservation Service. The main objective of this thesis work was to assess the effect of temperature on the soil water characteristic curve. The objective of this study was accomplished by following two different approaches. The first approach consisted of validating the equation proposed by Grant in 2005. This equation models the effect of temperature on soil suction. The second approach made use of statistical analysis in order to quantify the effect of the mean annual air temperature on suction, by analyzing data for more than 4,800 soils at different locations in the United States.

Thesis organization

Chapter 1 provides a brief introduction, including the thesis objectives and document organization.

Chapter 2 presents a detailed literature review including a description of the soil water characteristic curve, methods and equipment to measure suction, and its importance and applications. Chapter 2 also includes a brief summary on the importance of temperature effect on soil water retention.

Chapter 3 covers the existing proven models that relate soil suction and temperature; while Chapter 4 includes an assessment of the suction dependence on temperature described by the equation proposed by Grant in 2005 based on the van Genuchten SWCC equation. This analysis is based on the SWCC of soils with similar characteristics at different temperature zones.

Chapter 5 covers the statistical analysis of the temperature effect on suction for a sample of 4,800 soils at different temperature zones in the United States. A proposed simple model that includes the mean annual air temperature (MAAT) and soil properties is presented in this chapter.

Chapter 6 presents an attempt to assess the effect of the combined environmental effects represented by the Thornthwaite Moisture Index (TMI) on soil suction by utilizing statistical analysis.

Finally, Chapter 7 presents the conclusions with a brief summary of the results. Topics for future research related to the work accomplished and presented in this thesis are also presented.

## Chapter 2

## LITERATURE REVIEW

### Soil water retention characteristic of unsaturated soil

The soil-water characteristic curve illustrates the relationship of soil matric suction ($u_a$-$u_w$) and gravimetric water content w, or the volumetric water content θ, or the degree of Saturation $S_r$, and it is a measure of the water storage capacity of the soil for a given matric suction. The air entry value and high residual suction level can be derived from the SWCC. The shear strength, hydraulic conductivity, permeability function, chemical diffusivity, water storage, unfrozen volumetric water content, specific heat, and thermal conductivity are all functions of the SWCC. There are several devices to determine the SWCC in the lab and in field, such as; the suction plate, the pressure plate, filter paper, psychrometers, tensiometer, and gamma-ray beam attenuation. Some of these methods are used to measure the matric suction while others are used to measure the total suction.

SWCC is normally plotted on a semi-logarithmic scale for the suction range used in geotechnical practice. Figure 1 shows a schematic representation of the different components of the SWCC function.

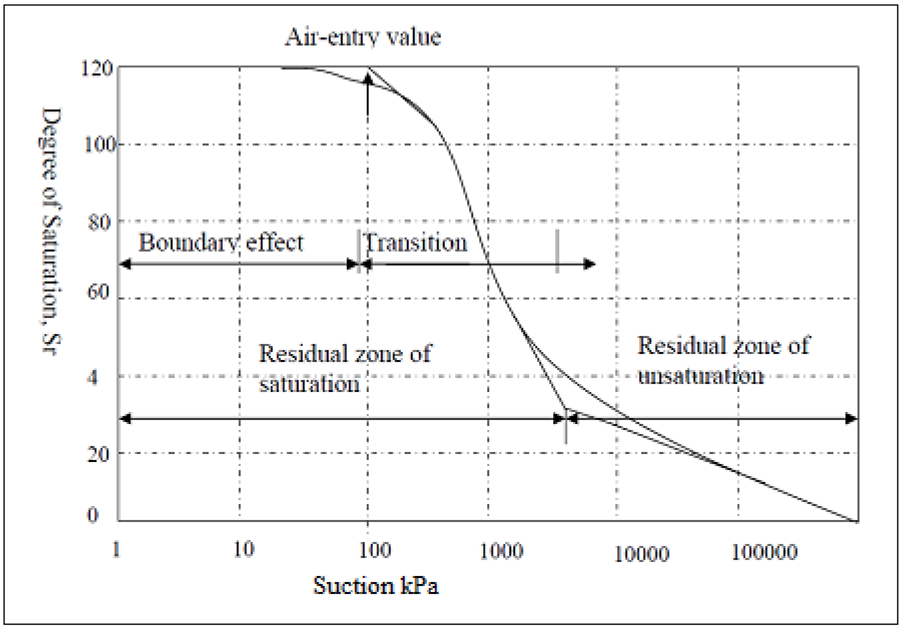


Figure 1 Soil water characteristic curves (Fredlund and Xing 1994)

The air entry value or bubbling pressure stands for the differential pressure between the air and water that is required to cause desaturation of the largest pores (Vanapalli and Fredlund 1996). It is important to know that the process of desaturation happens only at suction values greater than the air entry value. At high suction level (above 1,500 kPa), matric suction and the total suction can be analogous. At suction values smaller than the air entry value, the soil is considered to be saturated. The air entry value of the soil can be estimated by extending the constant slope portion of the soil water characteristic curve to intersect the suction axis at 100% saturation.

There are three identifiable stages of desaturation as shown in Figure 1: the boundary effect stage, the transition stage, and the residual stage of desaturation. In the boundary effect stage, water fills all the soil pores. The soil is saturated in this region, In the transition zone, the connectivity of the water in the voids or pores continue to reduce with increased values of suction, and eventually large increases in suction lead to relatively small changes in the degree of saturation. The residual state of saturation can be considered to be the degree of saturation at which the liquid phase becomes discontinuous. The residual state of saturation represents the stage beyond which it becomes increasingly difficult to remove water from a specimen by drainage (Vanapalli and Fredlund 1996).

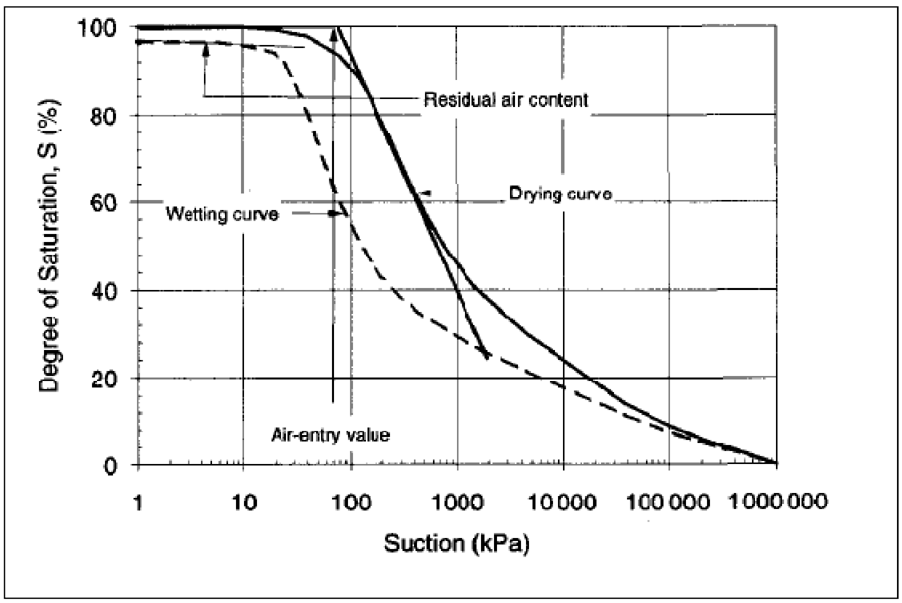


Figure 2 Hysteresis, desorption and adsorption curves (Vanapalli and Fredlund 1996)

The SWCC presents a hysteresis. Figure 2 illustrates this phenomenon where hysteresis causes the desorption curve and the adsorption curve to differ.  It is believed that the entrapped air may cause the end point of the adsorption curve differ from the starting point of the desorption curve. On the other hand, the total suction corresponding to zero degree of saturation appears to be the same for all soil types. A value slightly below $10^6$ kPa has been experimentally supported by research done in a number of different soils (Croney and Coleman 1961). This value is also supported by thermodynamic considerations (Richards 1965). In other words, there is a maximum total suction value corresponding to a zero relative humidity in any porous medium.

As the soil plasticity increases, the air entry value and the saturated water content increase. Therefore, for the same degree of saturation level, plastic soils have higher suction values than non-plastic soils.

The relationship developed between degree of saturation level and suction is based on the pore size distribution of the soil. That means that when the pore size distribution of the soil is either predicted or obtained, then the SWCC is uniquely determined from a general equation. Existing equations fit experimental data reasonably well over the entire suction range from 0 to $10^6$ KPa.

Many equations have been proposed to represent the SWCC. Most of these equations are empirical and are based on the shape of the SWCC. The most common equation is the one proposed by Fredlund and Xing (1994):

$$\theta = \theta_s \left[ \frac{1}{\ln\left[ e + \left( \psi / a \right)^n \right]} \right]^m \quad \text{……………………………………………….[1]}$$

Where $\theta$ is the volumetric water content, $\theta$ is a parameter closely related to the air entry value, and *n* and *m* are fixed parameters that control the slope of the SWCC. In general, the value of parameter $\theta$ is higher than the air entry value and corresponds to the suction value at the inflection point. However, for a small *m* value, the air entry value can be approximated by the parameter *a*.

The importance of the SWCC in different fields

The shape of the SWCC depends on the pore size distribution and compressibility of the soil. These two characteristics of porous materials are affected by the initial water content, soil structure, mineralogy, and the stress history (Lapierre et al. 1990; Vanapalli et al. 1999; Simms and Yanful 2000). Most SWCCs are S shaped. The curve shapes are a response to the pore size distribution of the material. For a rigid porous material of single pore size or uniform pore size distribution, whether it is a soil or not, the SWCC should be similar to the curve shown in Figure 1. However, complete water loss with suction increasing beyond the air entry value is not usual. In other words, it is difficult to remove all the water from a porous material by means of a small increase in suction (Fredlund and Rahardjo 1993). A material with a great number of pore sizes should present a more gradual reduction in water content with an increase in suction.

Suction changes due to moisture flow, and seepage control the strength and deformation behavior of unsaturated soils. Hence, accurate characteristic of moisture flow is often critical to both stability and deformation problems.

The expansive soil is a particular clay that is of special characteristics (i.e., swell–shrinking, crack and over-consolidation characteristics). The characterization of the expansive soil is strongly related to the change in suction. In general, the behavior of an unsaturated soil is strongly related to the pore size and pore geometrical distribution.

SWCC behavior can be a useful tool to understand the stabilization effects on expansive soils. A research experiment was conducted on expansive soil using two different types of fly ash (Lapierre et al. 1990; Vanapalli et al. 1999; Simms and Yanful 2000). The volumetric water contents of fly ash-treated soils decreased with an increase in the percentage of fly ash stabilizers. These changes are attributed to modifications in both particle size and moderate cementing effects in stabilized soils. The fine fly ash materials, similar to cement stabilizers, reduce pore void distribution of clayey soils by occupying their voids and also bond finer clay particles at contact points. As a result, fly ash-treated soils exhibit moderate to low plastic soil behavior with low volumetric moisture contents.

Methods to measure the soil suction

*Filter paper*

The filter paper method for total and matric suction measurements was originated in Europe in the 1920's and brought to the United States by Gardner in 1937. A filter paper in contact with the soil specimen allows water in the liquid phases and solutes to exchange freely and therefore, matric suction is measured. A filter paper that is not in contact with the soil specimen only permits water exchange in the vapor phase and therefore measures the total suction (Rahardjo and Leong 2006). The filter paper comes to equilibrium with the soil after several days in a constant temperature environment. An upper limit of 14 days equilibrium time is recommended although the recommendation might not be necessarily correct for clayey materials. After equilibration, the suction value of the soil and the filter paper is equal and the water content of the filter paper can be measured. The corresponding suction value can be inferred by using a filter paper wetting calibration curve developed with osmotic salt solutions. This method is based on the thermodynamic relationship between osmotic suction and the relative humidity.

*Psychrometers*

Thermocouple psychrometers can measure the soil total suction by measuring the relative humidity in the air phase of the soil pores or the region near the soil. The Peltier psychrometer is commonly used in geo-technical practice. It operates on the basis of temperature difference measurements between a non-evaporating surface (dry bulb) and an evaporating surface (wet bulb). The temperature difference is related to the relative humidity. Using Seeback effect and Peltier effect, the thermocouple psychrometer can measure the total suction in a soil sample by using the established calibration curve. This curve relates the microvolt outputs from the thermocouple and a known total suction value (Tang et al., 1997)

*Tensiometer*

Tensiometer utilizes a high air entry ceramic cup as an interface between the measuring system and the negative pore-water pressure in the soil. The high air entry porous ceramic cup is connected to a pressure measuring device through a small bore tube. The tube and the cup are filled with de-aired water. Then the cup is inserted into a pre-cored hole and keeps a good contact with the soil. Once equilibrium is established between the soil and the measuring system, the water in the tensiometer has the same negative pressures as the pore-water in the soil (Fredlund and Rahardjo 1993b). Thus, matric suction can be measured. Unlike the filter paper method and the axis-translation apparatus that can be only used in the laboratory, the tensiometers can be applied both in the laboratory and the field (Fredlund and Rahardjo 1993b).

*Pressure plate and pressure membrane*

The pressure plate and the pressure membrane are typically used to determine the matric suction ($u_a$-$u_w$), and the Soil-Water Characteristic Curve (SWCC). The main difference between the pressure plate and pressure membrane apparatus is that the pressure plate uses a ceramic porous disk (normally having the air-entry value of 1 bar, 3 bars, 5 bars or 15 bars) while the pressure membrane uses a cellulose membrane with an air-entry value of 15 bars. The suction equilibrium time is determined by the observation of the variation of the water level in a burette connected to the ceramic disk.

*Soil water retention curve determined by gamma-ray beam attenuation*

Practical problems still remain with the pressure chamber, e.g. (1) the difficulty of a correct judgment of equilibrium (2) the risk of changes in soil structure and water retention characteristics of the sample due to its frequent manipulation during measurements at each chosen potential and (3) the long time required for the whole process, mainly due to sample weighing and resaturation (also affected by hysteresis) after each equilibrium (Williams et al. 1992). The gamma ray beam attenuation method avoids the need of frequent sample manipulation as in the case of the pressure chamber method. The water content can be continuously monitored inside the chamber allowing a more precise judgment of the equilibrium. The time required for the retention curve determination can be significantly reduced in comparison with the traditional method. A schematic representation of this method is shown in Figure 3. This method is an adaptation of the conventional pressure chamber to permit the gamma-ray beam to pass through the soil sample inside the chamber, allowing for continuous soil moisture monitoring during the whole process of soil water retention measurements, without the opening of the chamber for measurements at each step. This new improvement leads also to a more precise judgment of equilibrium, since soil moisture is continuously monitored inside the chamber. Sample manipulation is eliminated since it is saturated only once at the beginning of the process, minimizing the risk of modifications in structure and, as a consequence, the time required for the whole water retention curve establishment is shortened (Bacchi et al. 1998).

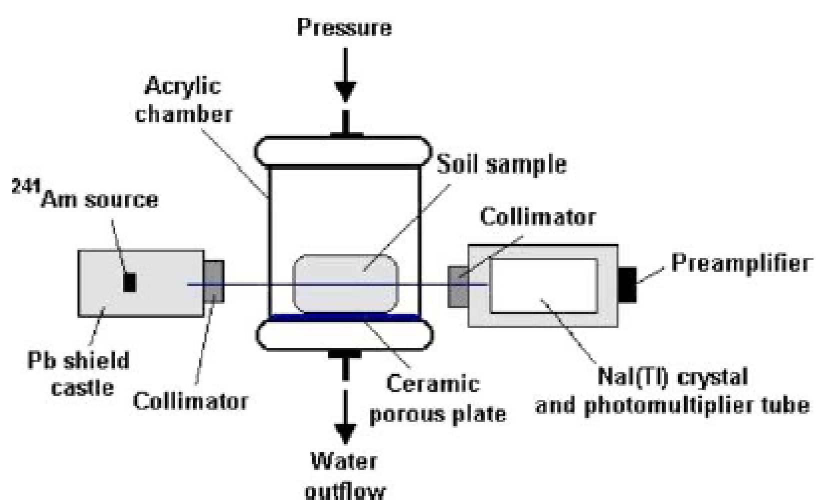


Figure 3 Scheme of the gamma-ray beam attenuation system to valuate soil water retention curves (Williams et al. 1992)

The nuclear method presents some advantages over the traditional method including the higher accuracy in the determination of time of equilibrium and the reduction in the time required for the whole retention curve determination. This is because the soil sample in the nuclear method is submitted only one time to the wetting and drying processes.

*Measurement of soil-water characteristic curves for fine-grained soils using a small-scale centrifuge*

Commercially available small-scale centrifuges can be used to obtain multiple water contents versus suction data points for the soil-water characteristic curve at a single speed of rotation.

A high gravity field is applied to an initially saturated soil specimen in the centrifuge. The soil specimen is supported on a saturated, porous ceramic column. The base of the ceramic stone rests in a water reservoir that is at atmospheric pressure conditions. The water content profile in the soil specimen after attaining equilibrium is similar to water draining under in situ conditions to a groundwater table where gravity is increased several times.

The time period for measuring the soil-water characteristic curves for fine-grained soils reduces considerably using the centrifuge method in comparison to conventional testing procedures such as the pressure plate apparatus or a pressure cell. (Khanzode et al, 2002)

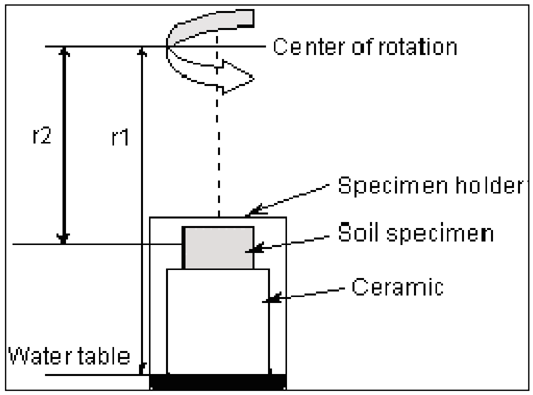


Figure 4 Small-scale centrifuge

The importance of the temperature effect on the soil water retention

Previous studies have shown that part of the influence of temperature on both water retention characteristics and the hydraulic conductivity function is attributed to changes in soil-water properties based on theoretical considerations for free water. The liquid phase flux is expressed by the extension of Darcy's law:

$$q_l = -\frac{k_i k_r}{\mu_l}(\nabla p_l - \rho_l g) \quad \text{[2]}$$

Where $q_l$ is the liquid phase flux, $k_i$ is the intrinsic permeability, $k_r$ relative permeability, $\mu_l$ is dynamic water viscosity, $g$ is the gravitational acceleration vector and the $\rho_l$ is the matric pressure (pressure difference between the liquid and the gas phase ). In this equation, $\mu_l$ and $\rho_l$ are considered to be temperature dependent as shown in Figure 5.

| Temperature dependence of physicochemical properties of water[a] | |
|---|---|
| Property | Relationship |
| Density ($kg/m^3$)[b] | $\rho_L = 658.2 + 2.509T - 4.606 \times 10^{-3}T^2$ |
| Dynamic viscosity (Pa s)[b] | $\ln \mu_L = -6.434 - \frac{2414}{T} + \frac{667,300}{T^2}$ |
| Surface tension (N/m)[c] | $\sigma = 0.117 - 0.000153T$ |
| Vapor diffusion coefficient in air ($m^2/s$)[d] | $D_G = 2.92 \times 10^{-5}\left(\frac{T}{313\ K}\right)^{2.0}$ |

Figure 5: Temperature dependence of physicochemical properties of water (Grifoll 2005)

From the physicochemical properties of water, the density, the dynamic viscosity, the surface tension, and the vapor diffusion coefficient are temperature dependent properties. There are different theories to describe the effect of temperature on the water phase in the unsaturated soil as discussed in later sections of this work.

The thermal conductivity of water increases slightly with increasing temperature. The thermal conductivity of saturated pore air increases markedly with increasing temperature .An increase in temperature should cause an increase in the diffuse layer thickness and a decrease in the surface potential for a constant surface charge with all other factors constant. However an increase in temperature results also in a decrease in dielectric constant owing to the increased energy needed to polarize fluid molecules as temperature increase (Mitchell and Soga 2005)

# Chapter 3

# SUCTION TEMPERATURE DEPENDENCE MODELS

## Theories explaining the temperature effects on soil water retention

Different theories have been proposed to explain the relation between temperature and soil suction. Considering soil water composed of continuous water and isolated packets of water, the continuous water content change linearly with the total water content. When temperature increases, water flows from isolated packets to the continuous water phase. This results in a shift in the SWCC. Also there are additional factors contributing to temperature effect on the SWCC such as entrapped air and difference between surface tension of the soil solution and pure water. Entrapped air may play a role in the temperature coefficient of the soil water pressure head, which includes the effect of entrapped air. Entrapped air volume is expected to decrease with decreasing water content, because a large number of pores become part of the continuous air phase.

Hopmans and Dane (1986b) measured the water retention curve corresponding to the total entrapped air volumes and the surface tension of the soil solution at two temperatures. The study showed that the effect of entrapped air volume decreased the effect of temperature on the water retention curve.  The authors demonstrated that ignoring temperature effects on soil hydraulic properties can result in substantial prediction error in water movement (Hopmans and Dane 1985).

Liu and Dane proposed a theory that assumes that the soil water forms a continuum and the isolated water packets do not contribute to soil hydraulic equilibrium (Liu and Dane 1993). If water inside a capillary tube is in hydraulic equilibrium, then:

$$L = \frac{2\sigma(\frac{1}{R1} - \frac{1}{R2})}{\rho g} \qquad [3]$$

Where $\sigma$ is the surface tension coefficient, $L$ is the distance between the two air-water interfaces, $R1$ and $R2$ are the radii of the curvature at the two air-water interfaces, $\rho$ is the density of the water, and $g$ is the gravitational field strength. As the temperature increases, the interfacial tension will decrease and then the capillary tube will not be able to hold all entrapped water. Increasing the temperature may also cause entrapped water to become connected with continuous water. The attractive forces between water and solid surfaces decrease with increasing temperature, and thus the isolated water content decreases. Increasing temperature will also lead to reduction in the residual water content value (Hopmans and Dane 1986a).

Assuming that the capillary pressure head ($h$) of soil water is defined by the continuous water phase alone and not by the total water content. Isolated water packets that contribute to the total water content but may have a different potential than the continuous water will therefore have no bearing on the soil water pressure head. The relationship between the total water content, isolated water content, and the continuous water content is defined by the following equations [4]  (Liu and Dane 1993).

$\theta t = \theta s + \theta c$

$\theta c = 0$ when $\theta t = \theta r$

$\theta c = \theta s$ when $\theta t = \theta s$

$$\Delta\ \theta t = \theta t,1 - \theta t,2 = \frac{\theta s - \theta t,1}{(\theta s - \theta r,1)(\theta r,1 - \theta r,2)} \quad \text{……………………………[4]}$$

Where $\theta c$ is the continuous volumetric water content, $\theta s$ is the isolated volumetric water content, $\theta r$ is the residual volumetric water content, $\theta s$ is the isolated volumetric water content, and $\theta t$ is the total volumetric water content.

For a given $\theta c$, the pore water configuration is unchanged. Hence, it is safe to assume that the changes in pressure head, when the temperature changes, is due to changes in surface tension if $\theta c$ remains unchanged (Liu and Dane 1993).

$$h(\theta c, j) = \frac{2\sigma(Tj)}{\rho g r j} \quad (j=1,2) \quad \text{………………………………………………[5]}$$

Where *r* is the radius of equivalent capillary tube, *h1* and h2 are the water pressure head values at *T1* and *T2* for the same $\theta c$, respectively, and *α (T1,T2)* is the temperature coefficient,

$$\frac{h2(\theta c,1)}{h1(\theta c,2)} = \frac{\sigma(T2)}{\sigma(T1)} = \alpha(T1,T2) \quad \text{………………………………………………[6]}$$

Where *α(T1,T2)* is the temperature coefficient.

Using this theory, the soil water retention curve (SWCC) at different temperatures can be easily calculated. *To* calculate the SWCC at *T2*, the SWCC at reference temperature *T1* and the residual water content need to be known. The residual water content at *T2* also needs to be known. Assuming the same volumetric water content at *T1* and *T2* and applying the following equation [7]:

$$\Delta\ \theta t\ = \theta t\ , 1 - \theta t, 2 = \frac{\theta s - \theta t,1}{(\theta s - \theta r,1)(\theta r,1 - \theta r,2)} \text{..............................[7]}$$

We can calculate $\theta t, 2$ from $\theta t, 1$ (assuming $\theta c$ is the same). Finally, the soil water pressure head $h2$ can be calculated from the following equation:

$$\frac{h2(\theta c,1)}{h1(\theta c,2)} = \frac{\sigma(T2)}{\sigma(T1)} = \alpha(T1,T2) \text{............................................[8]}$$

Where *h1* and h2 are the water pressure head values at *T1* and *T2* for the same $\theta c$, respectively, and *α (T1,T2)* is the temperature coefficient. The equations above apply to soil water pressure heads at two different temperatures for the same continuous water content, if $\theta s$ does not vary with temperature. However, the total water content differs from the continuous water content by a constant for a given $\theta t$ according to the first equation, regardless of temperature variations. Subsequently, equation [8], holding for the same continuous water content, can also be applied to the same total water content at different temperatures.

Models available to estimate moisture flow under the effect of temperature in unsaturated soils

*Non-isothermal models*

The liquid content, the matric pressure and the soil water-characteristic curves are usually reported, in most studies, at a temperature of 20°C. In this isothermal model, the total volumetric water content $\theta_L T$ is considered to be the result of contributions of continuous and funicular water regions, where the funicular water regions being dependent on the reference volumetric water content which is temperature dependent. The saturation and residual water content used in this equation are also temperature dependent. This temperature- dependent volumetric content can be expressed as:

$$\theta_L T = \theta_L(T_0) - \frac{\theta_{LS} - \theta_L(T_0)}{\theta_{LS} - \theta_{LR}(T_0)}\left[\theta_{LR}(T_0) - \theta_{LR}(T)\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [9]$$

Where, $T$ is temperature, $T_0$ .is the reference temperature, and $\theta_{LR}(T_0)$ is the residual volumetric content at the reference temperature $T_0$ .

It is noted that $\theta_L T$ , and $\theta_L(T_0)$ would correspond to the same matric pressure if surface tension dependence on temperature is neglected. Although it is known that, for a given continuous water content, the matric pressure will be affected by the variation of surface tension with temperature as proposed by equation [10]:

$$Pl(T) = Pl(T_0)\frac{\sigma(T)}{\sigma(T_0)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [10]$$

Where $\sigma(T)$ is surface tension calculated as a function of temperature given by equation given in Figure [5]. Therefore as implied by equations [9] and [10], water saturation at a given temperature has a correspondingly unique matric pressure. A linear relationship showing the dependence of the $\theta_{LR}$ on temperature follows equation [11].

$$\frac{\theta_{LR}(T)}{\theta_{LR}(293K)} = 1 - a(T - 293K) \qquad [11]$$

Where $a$ is an empirical constant that can vary with the specific soil properties under consideration. However, an analysis of data for three soils revealed a weak dependence of $a$ on soil type (Grifoll et al. 2005).

*Another theory explaining the effect of temperature on the retention curves proposed by (W. Wu et al., 2004)*

The temperature effect on the hydraulic properties of porous media can be classified into two different types depending on the dimension of the pore space and its interaction with the soil matrix. These types are; the inter-aggregate water (bulk water or free water which can flow in the normal condition) and the intra-aggregate water (weakly bonded diffuse-layer water and strongly bonded crystal water). The inter-aggregate water is distinguished from the intra-aggregate water mainly according to the pore water velocity. Adsorbed water cannot flow under normal thermal condition, whereas the bulk water is mobile due to water pressure gradient in the pore space. However, part of the adsorbed water will be converted to the bulk water with the development of temperature.

The suction decreases with increasing temperature under constant degree of saturation. The sensitivity of the suction to temperature changes at certain constant value of the water content is given by the following equation:

$$\left(\frac{\partial s(w)}{\partial T}\right) = \frac{s(w)}{a_1 + b_1 T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[12]$$

Where $T$ is temperature, $s$ is suction, $a_1$ and $b_1$ are empirical functions depending on water content. An explicit solution to equation [12] that predicts the suction development was obtained as shown below:

$$\frac{s(w,T)}{s(w,T_r)} = \left(\frac{a_1(w) + b_1(w)T}{a_1(w) + b_1(w)T_r}\right)^{b_1(w)} = \left(\frac{a_1 + b_1 T}{a_1 + b_1 T_r}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[13]$$

Where $T_r$ is the reference temperature. It is noted that temperature is not the unique factor affecting the suction variations, especially at the high suction state. When combining equation [13] and the retention curve equation proposed by Fredlund and Xing, a new retention curve between the degree of saturation and suction under given temperature is obtained as shown in equation [14] (W. Wu et al., 2004):

$$S_{r,w} = C(s)\left(\frac{1}{1+(\alpha_T S)^n}\right)^{m_r}, \alpha_T = \alpha\left(\frac{a_1 + b_1 T_r}{a_1 + b_1 T}\right)^{b_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[14]$$

Where $S_{r,w}$ is the degree of saturation, $\alpha$, $m_{r,n}$ are the parameters related to the air entry value of the soil, the residual water content and the slope of the suction-saturation curve at the air entry value of the soil, respectively; and $C(s)$ is a parameter related to suction.

Previous studies on the effect of temperature on the SWCC and their limitations

Wenhua et al. (2004) conducted studies on the effect of temperature on the SWCC. This research was conducted on compacted silt samples using modified triaxial equipment. Isothermal and non-isothermal tests were conducted. The temperature values applied were 25˚C, 40˚C, and 60˚C, and suction values varied from 0 to 300 kPa. Results from the temperature controlled SWCC (soaking and desaturation) tests clearly showed that the degree of saturation was reduced with increasing temperature. This is due to the reduction of the surface tension of water with increasing temperature, which in turn reduces the air entry value. Owing to the air entry dependence of the effective stress, the effective stress decreases with increasing temperature (Uchaipichat and Khalili 2009). These experiments were conducted in a suction ranging from 0 to 300 kPa, which is very limited. The effect of temperature on the SWCC at higher suction values was not assessed even though it was suggested that temperature had greater effect at low moisture content values.

The same authors also presented a case study on Boom clay. Results showed that for a given water content, the total suction at $20^{o}$C was higher than at $80^{o}$C due to the change in the capillary component of suction, which was attributed to the change in surface tension of water, the change in clay fabric, and the change in the pore-water chemistry of the clay. It is worth noted that the change in clay fabric and the pore water chemistry due to temperature changes is expected to be irreversible. This study concluded that the change in clay fabric and the pore water chemistry do not affect the total suction magnitude for clays with low organic content for the range of temperatures used (20$^o$C to 80$^o$C); and therefore, the change in total suction due to temperature may be caused by the change in the capillary component of suction or the inaccuracy of the device used.

*Models available for the temperature effect on the hydraulic conductivity*

Hydraulic conductivity is inversely proportional to the viscosity of the fluid. The viscosities of fluids, including that of water, decrease proportionally to the exponent of the reciprocal of temperature so that hydraulic conductivity increases with increasing temperature. Therefore, the absolute value of the matric potential decreases linearly with temperature (Grant, 2005).

Empirical relations such as the van Genuchten equation relates soil water content to matric potential:

$$S_e = \left[ \frac{1}{(\alpha\psi)^n + 1} \right]^{\frac{n-1}{n}} \quad \text{[15]}$$

Where $S_e$ is the water saturation defined by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad \text{[16]}$$

Where $\theta$ is the volumetric water content, $\theta_s$ is the saturated water content, $\theta_r$ is the residual water content, and $\alpha$ and $n$ are fitted parameters.

The Van Genuchten equation can be used to calculate the relative permeability of the porous medium as a function of degree of saturation:

$$k_r = K/K_s = S_e^{1/2}\left[\frac{\int_0^{s_e}\frac{dx}{\psi(x)}}{\int_0^1\frac{dx}{\psi(x)}}\right]^2 \quad\text{……………………………………………….[17]}$$

Where $k_r$ is the relative hydraulic conductivity, $K$ is the unsaturated hydraulic conductivity, and $K_s$ is the saturated hydraulic conductivity.

It is expected that the effect of temperature on soil water characteristics, at room temperature, for an average soil decreases 0.8% for every 1K increase in temperature. Using Grant model illustrated in equation [19], the surface tension of water also decreases linearly with temperature. This relation is best described using equation [18] (Grant, 2005):

$$\psi(T) = \psi(T_r)\frac{\beta_0 + T}{\beta_0 + T_r} \quad\text{…………………………………………………[18]}$$

Where $T_r$ is a reference temperature, $\beta_0$ is a constant which in most soils is believed to be a value between -350 and -450 K. Grant (2005) argued that for his experiments, $\beta_0$ is unaffected by soil water content.

Adapting equation [18] in van Genuchten equation will result in the matric potential at a reference temperature, which can be described as:

$$S_e = \left\{ \frac{1}{\left[ \alpha\psi \left( \frac{\beta + T_r}{\beta + T} \right) \right]^n + 1} \right\}^{\frac{n-1}{n}} \quad \text{……………………………..…………[19]}$$

Accordingly, the effect of increasing temperature is to decrease the matric potential gradients (Grant, 2005).

*Effect of temperature on hydraulic conductivity*

The hydraulic conductivity is directly proportional to liquid density, the reciprocal of liquids viscosity, and the square of the mean grain diameter.

$$K = \frac{k\rho g}{\eta} \quad \text{…………………………………………………………….[20]}$$

Where $\rho$ and $\eta$ are the density and viscosity of the liquid, *g* is the gravitational constant, and *k* is the intrinsic permeability of the porous matrix

The water and the energy transport in a non-isothermal soil is governed by the following equations:

$$\frac{\partial\theta}{\partial t} = \nabla \bullet (D_T \nabla T) + \nabla \bullet (D_W \nabla \theta) - \frac{\partial K}{\partial z} \quad \text{…………………………………[21]}$$

$$C_v \frac{\partial T}{\partial t} = \nabla \bullet (k \nabla T) - L \nabla \bullet (D_w \nabla \theta) \quad \text{……………………………..……….[22]}$$

Where t is the time in seconds, $D_T$ thermal water diffusivity, $D_W$ water content –based water diffusivity, $z$ depth, $C_v$ volumetric heat capacity, $k$ apparent thermal conductivity of the soil, and $L$ latent enthalpy of vaporization. The total volumetric water content is the sum of the liquid and gas water contents. The use of these equations requires the knowledge of four relationships to describe the properties of the soil in the system (Mitchell and Soga, 2005): 1) hydraulic conductivity as a function of water content; 2) thermal conductivity as a function of water content; 3) volumetric heat capacity; and 4) suction head as a function of water content.  This approach is only applicable to homogenous and isotropic porous media, and has several shortcomings: it assumes the soil volume will remain constant, it cannot account for flow due to the changes in total stress, and the water flow is in response to moisture content gradients (rather than gradients in head), which implies that the soil is homogeneous.

## Chapter 4

## ANALYSIS AND VALIDATION OF EXISTING MODELS

This Chapter presents the analysis of the model presented by Grant in 2005. This model incorporates temperature effects on the SWCC as presented before. In order to analyze the model, a database collected from the NRCS was used. Details of the database and the analysis are given below.

### Database selection and processing

The database used to study the effect of temperature on soil water retention contained around 4,800 surface soils from all over the USA. The database was obtained from the National Resources Conservation Service (NRCS). The NRCS has the objective of collecting, storing, maintaining, and distributing the soil survey information for private land owner in the United States, particularly the State Soil Geographic (STATSGO) database. This data consist of soil map units that are linked to attributes in order to indicate the location of each soil map unit and its soil properties. The “map units” are areas that represent a group of soil profiles with generally the same or similar characteristics.

The tabular data contained in the database represent a mean range of properties for the soil comprised in each soil map unit. Information for more than 9,000 soil profiles covering the entire United States were collected and organized by Gustavo Torres at Arizona State University (Torres, 2011).

The mean annual air temperature (MAAT) required for this analysis is not included in this database.  The GIS mapping system was used to locate the soils in order to find out the MAAT. Once the longitude and latitude for each sample was identified, the GIS mapping system was again used to extract the MAAT for each soil.

Properties available for each soil unit

The soil properties included in the database to estimate the SWCC parameters are the volumetric water content at 10, 33, and 1,500 kPa; and the saturated volumetric water content (i.e., satiated water content or porosity). In addition, parameters such as grain-size distribution values, consistency limits, saturated hydraulic conductivity, groundwater table depth and bedrock information were included.

*Temperature effect evaluation*

The soils were divided into groups of similar properties.  The properties chosen to represent the soil were the percent passing #200 US sieve (Passing200) and the Plasticity Index (PI). Soil families included soils with Passing 200 ranging from 20-100% and PI value ranging from 0-12.5%. Soil groups with PI values higher than 12.5% were considered, but the data found did not have enough soils in different regions and therefore, families of highly plastic soils were not available, as shown in Figures 6 and 7. However, the entire database was taken into consideration in the statistical analysis approach described in Chapter 5.

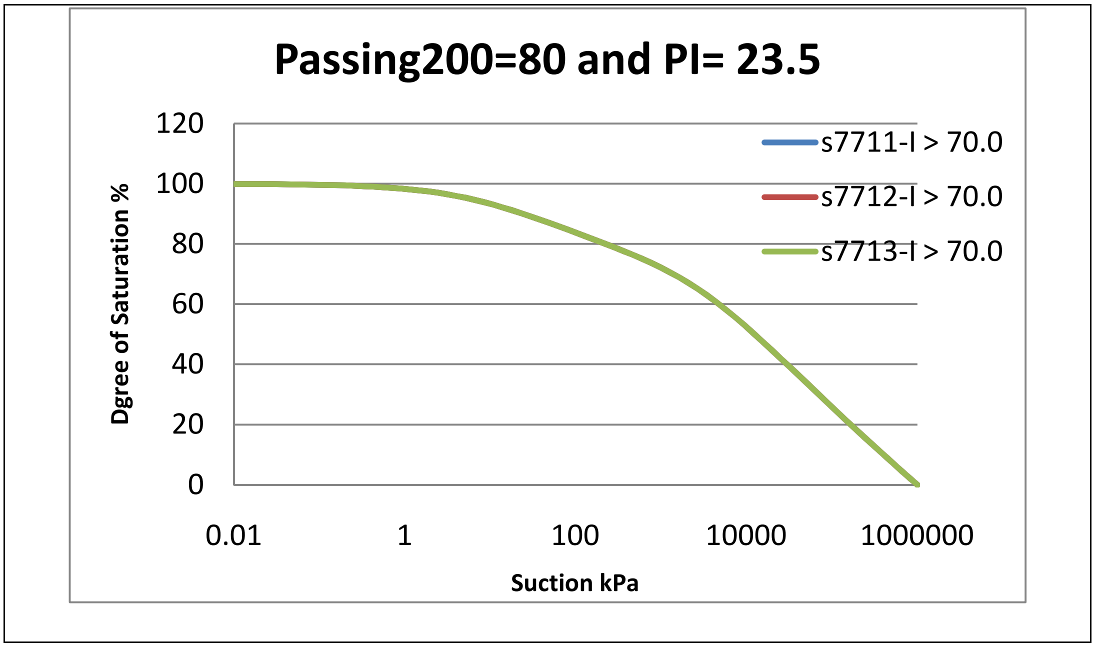


Figure 6 A family with Passing200=80 and PI= 23.5

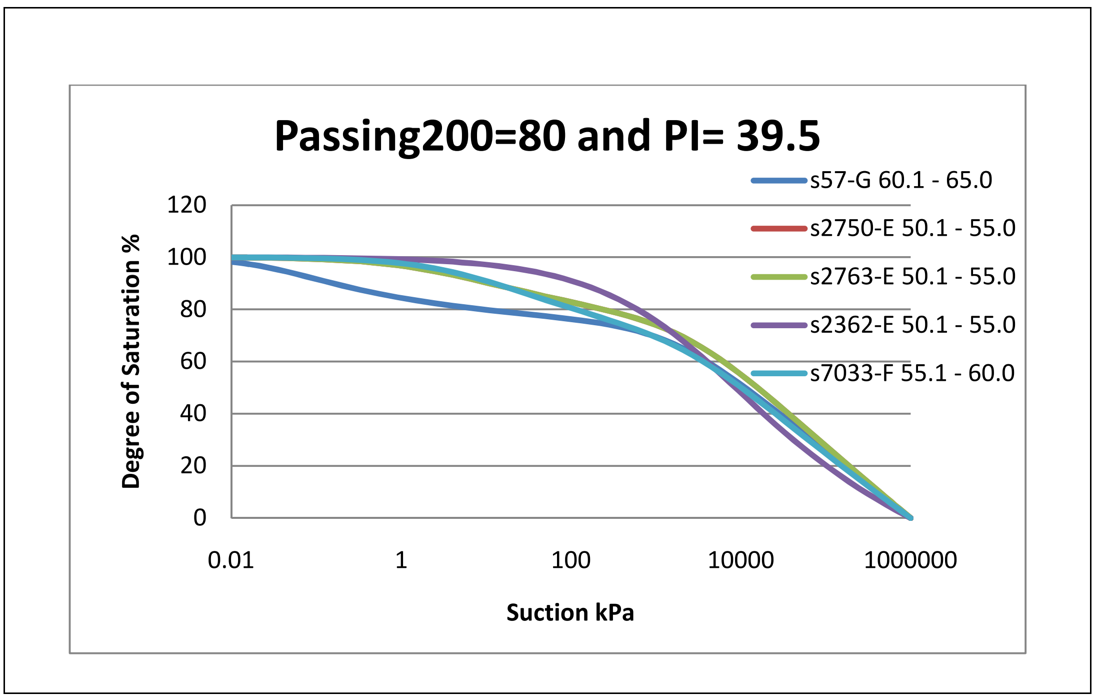


Figure 7 A family with Passing200=80 and PI= 39.5

Twenty (20) groups were recognized to contain soil with similar index properties. Each group included about 200 soils, but most of them were located in the same region. For each group, the SWCC plots were drawn and one or two representative soils were chosen for each location. In that way, each group of soils was reduced to soils located in regions with different mean annual air temperature (MAAT). The mean annual temperature map for the US is presented in Figure 8. Soils representing regions with MAAT as low as 30F and as high as 70F, and in between, were included in the analysis.

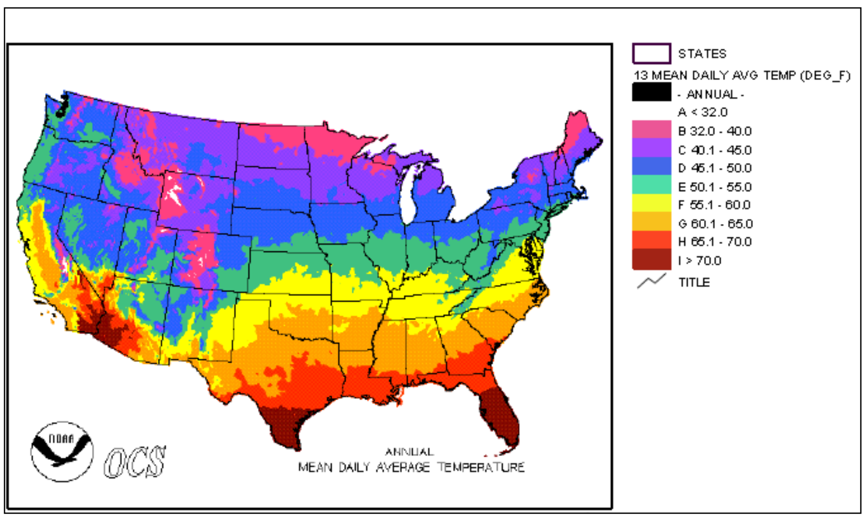


Figure 8 Mean annual air temperature map (NOAA)

For each family of soils, the soil water characteristic curves were plotted on the same graph to find any possible relation between MAAT and the soil water characteristic curve. As stated before, each group consisted of soils with similar PI and Passing200 values but different MAAT. By keeping all other significant factors identical, it was possible to isolate the effect of temperature.

More than 20 groups of soils were selected and plotted for this analysis. A sample plot for a group of soils with PI = 7.5 and Passing200= 60 is shown in Figure 9. The graphs and tables for the 20 groups used in this analysis are included in Appendix B.

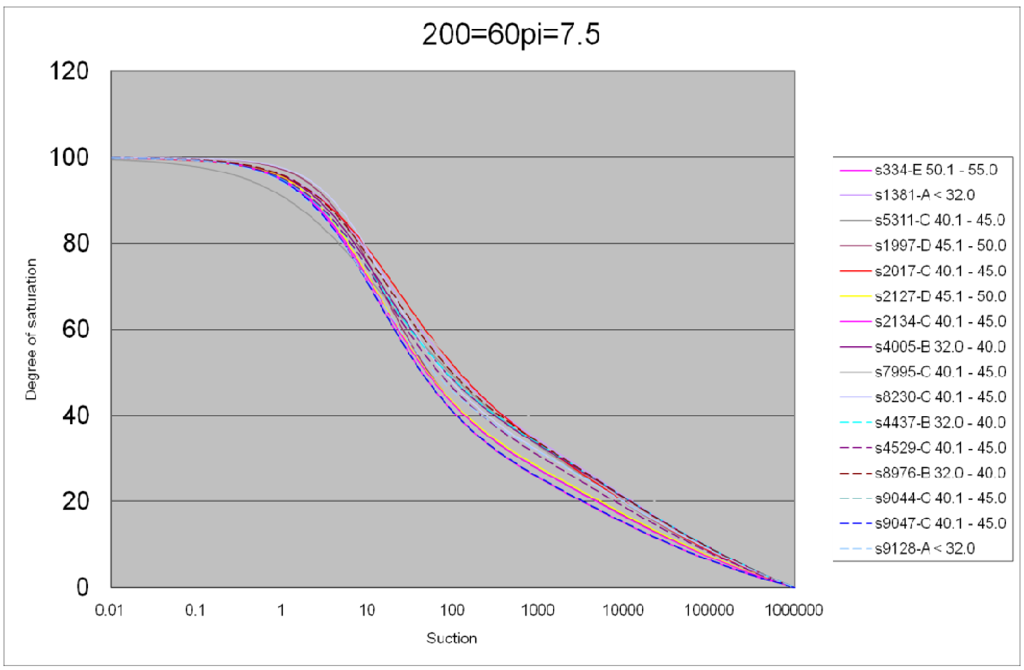


Figure 9 SWCCs for Passing 200=60 and PI=7.5

<u>Results and analysis</u>

Several observations were noted in these plots. Most significantly, a clear inverse relationship between temperature and suction was observed. Moreover, the effect of temperature is more evident at lower degree of saturation levels. Lastly, suction levels for soils with higher PI had notably higher suction values.

Since the variation of suction due to temperature is not the same at different degree of saturation levels; the degree of saturation level was chosen to be 20%, as it represents the residual condition in soil.

Suction values at the 20% degree of saturation level for each soil in the group were calculated using the Excel® goal seek function. The suction was then plotted versus mean annual air temperature (MAAT) as shown in Figure 10 and the relationship was modeled with the polynomial equation for the curve. It was noted that the relations between temperature and suction were different for groups with different PI value.

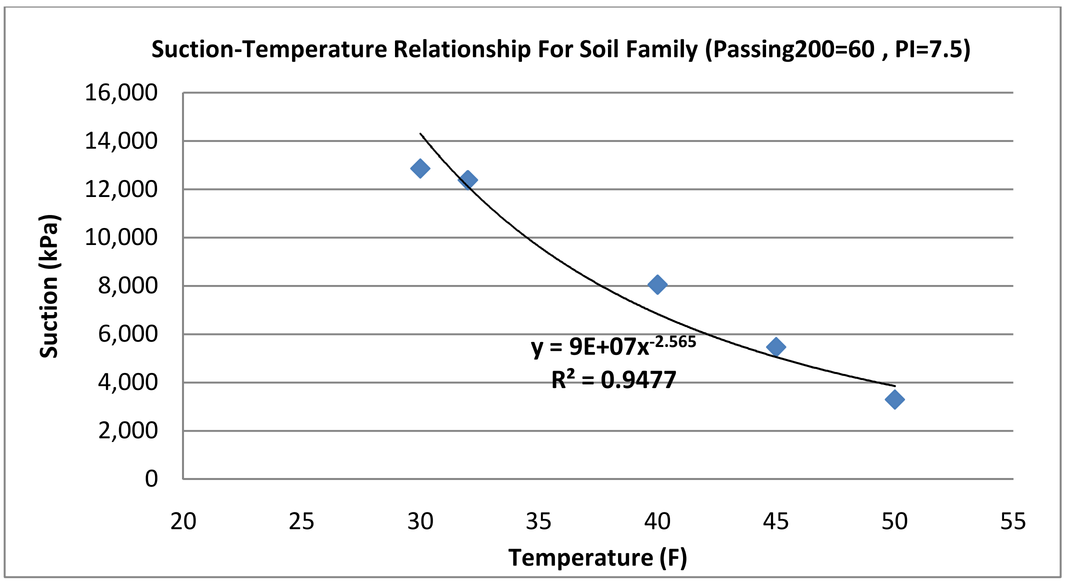


Figure 10 Relation between temperature and suction for soils with passing 200=60

Table 1 presents the equations found for each group of soils. The first column shows the family of soil according to its passing 200 classification and the second column shows the range of PI values. For each PI value, an equation was derived (third column) representing the relation between temperature and suction for this particular family. The fourth column shows the $R^2$ value for the equation. To calculate the suction from Grant equation a reference temperature was needed. 70 degree F was chosen to be the reference temperature used in Grant equation as noted in column 5. The resulting suction calculated from the derived equations at temperatures of 65, 60, 55, 50, 45, 40 F are presented in columns 6 through 11.

<u>Comparison with Grant model for temperature effect on suction</u>

In order to evaluate the effect of temperature versus that modeled in the Grant equation, the suction values at the reference temperature were calculated using the derived equations. Using this suction value as a reference, the suction values at temperatures 40F, 45F, 50F, 55F, 60F and 65F were calculated using the derived equation and the Grant equation with $\beta_0$ = -350K. Comparison plots were created for each soil group as shown in Figure 11. For all groups of soils, it was observed that the decrease in suction resulting from the increase in temperature was greater in case of the derived equation, which suggested a smaller $\beta_0$ value than that proposed by Grant. It was also observed that $\beta_0$ is not a constant but a function of temperature.

Table 1 Comparison between existing and calculated equations

| | PI | Derived Equation | $R^2$ | suction at T=70F using equation | suction at T=65 | suction at T=60 | suction at T=55 | suction at T=50 | suction at T=45 | suction at T=40 |
|---|---|---|---|---|---|---|---|---|---|---|
| Passing 200 = 20 | 0 | $s = 2 \times 10^{12} \times T^{-5.894}$ | 0.6271 | 26.6699 | 41.3 | 66.2 | 110.5 | 193.8 | 360.6 | 721.9 |
| | 2.5 | $s = 4 \times 10^{16} \times T^{-7.892}$ | 0.9998 | 109.8 | 197.0 | 370.6 | 736.4 | 1562.4 | 3588.4 | 9090.8 |
| | 7.5 | $s = 1 \times 10^{08} \times T^{-2.456}$ | 0.9447 | 2940.6 | 3527.6 | 4294.0 | 5317.0 | 6719.4 | 8703.8 | 11623.6 |
| Passing 200 = 30 | 0 | $s = 5 \times 10^{22} \times T^{-12.27}$ | 0.9934 | 1.5 | 3.8 | 10.1 | 29.3 | 93.7 | 338.7 | 1425.1 |
| | 2.5 | $s = 2 \times 10^{09} \times T^{-3.348}$ | 0.8593 | 1329.4 | 1703.7 | 2227.3 | 2980.5 | 4100.9 | 5835.5 | 8656.3 |
| | 5 | $s = 2 \times 10^{10} \times T^{-3.934}$ | 0.7315 | 1102.6 | 1475.8 | 2022.0 | 2847.4 | 4142.7 | 6270.4 | 9966.1 |
| Passing 200 = 40 | 2.5 | $s = 8 \times 10^{10} \times T^{-4.235}$ | 0.8013 | 1227.7 | 1680.4 | 2358.4 | 3409.2 | 5104.5 | 7975.1 | 13133.1 |
| | 5 | $s = 91056 \times T^{-0.82}$ | 0.1234 | 2794.7 | 2969.7 | 3171.2 | 3405.7 | 3682.6 | 4014.9 | 4422.0 |
| | 7.5 | $s = 1 \times 10^{10} \times T^{-3.567}$ | 0.9364 | 2621.4 | 3414.6 | 4542.9 | 6196.2 | 8705.1 | 12676.3 | 19295.3 |
| Passing 200 = 50 | 2.5 | $s = 144.92 \times T^{-0.139}$ | 0.966 | 80.3 | 81.1 | 82.0 | 83.0 | 84.1 | 85.4 | 86.8 |
| | 5 | $s = 3 \times 10^{08} \times T^{-2.824}$ | 0.9872 | 1847.4 | 2277.5 | 2855.1 | 3650.4 | 4777.8 | 6433.5 | 8972.3 |
| | 12.5 | $s = 2 \times 10^{08} \times T^{-2.443}$ | 0.8014 | 6215.2 | 7448.7 | 9057.5 | 11202.7 | 14139.9 | 18290.8 | 24389.2 |
| Passing 200 = 60 | 3.5 | $s = 3 \times 10^{11} \times T^{-4.874}$ | 0.7921 | 304.9 | 437.5 | 646.3 | 987.6 | 1571.6 | 2626.4 | 4663.2 |
| | 5 | $s = 5 \times 10^{06} \times T^{-1.764}$ | 0.9218 | 2781.1 | 3169.5 | 3650.2 | 4255.7 | 5034.9 | 6063.2 | 7463.4 |
| | 7.5 | $s = 9 \times 10^{7} \times T^{-2.565}$ | 0.9477 | 1665.6 | 2014.3 | 2473.3 | 3091.8 | 3948.1 | 5173.1 | 6997.8 |
| Passing 200 = 70 | 5 | $s = 2 \times 10^{6} \times T^{-1.427}$ | 0.6896 | 4656.7 | 5176.1 | 5802.4 | 6569.5 | 7526.6 | 8747.7 | 10348.8 |
| | 9-10 | $s = 106193 \times T^{-0.555}$ | 0.1086 | 10047.7 | 10469.6 | 10945.2 | 11486.7 | 12110.6 | 12839.9 | 13707.3 |
| Passing 200 = 80 | 7.5 | $s = 8 \times 10^{11} \times T^{-4.68}$ | 0.6856 | 2604.0 | 3661.7 | 5291.7 | 7896.3 | 12241.3 | 19875.2 | 34167.5 |
| | 10 | $s = 7 \times 10^{11} \times T^{-4.434}$ | 0.8012 | 4612.5 | 6406.8 | 9136.4 | 13437.9 | 20505.3 | 32715.5 | 55152.3 |

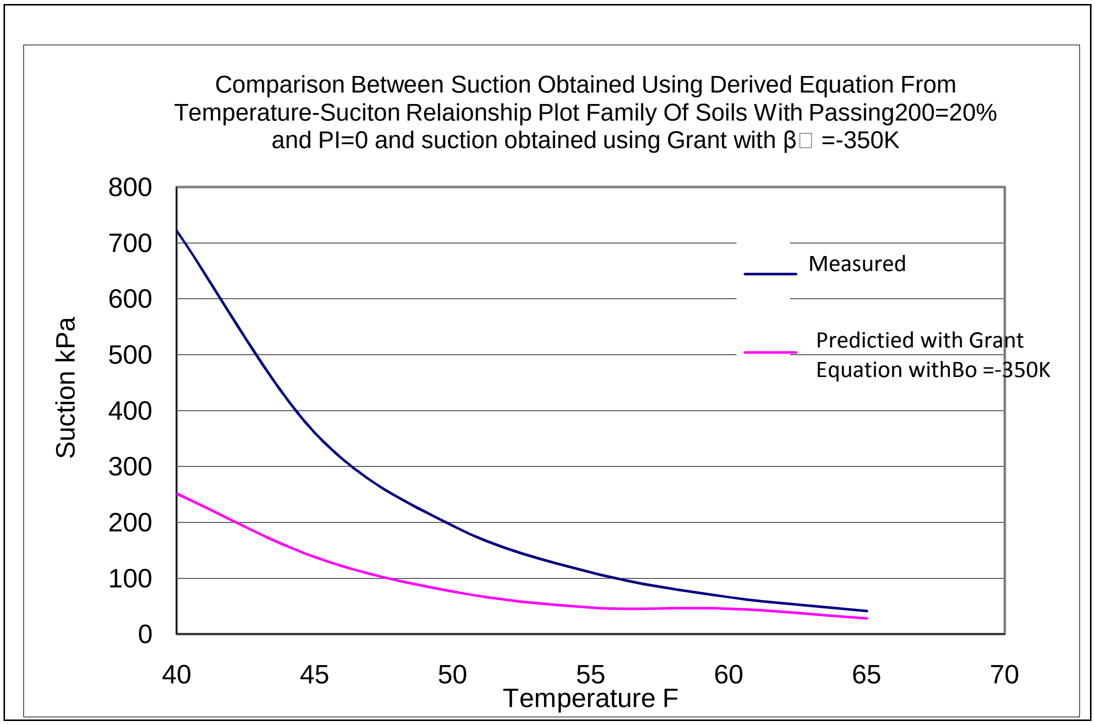


Figure 11 Measured suction-temperature relationship versus predicted relationship from Grant model for one family of soils

Assessment of the range of $\beta_o$ parameter value suggested by Grant

In order to evaluate if the Grant equation would fit the database gathered for this research project, an assessment of the range of $\beta_o$ values obtained with the database SWCCs at different MAAT was attempted. To that extent, the Grant equation was used to replace both the reference suction at $T_r$ and required suction at $T$. These suction values were calculated using the relationship found between MAAT and suction for each group of soils (shown in Table 1). The following steps were followed in this procedure:

1) The suction values at the reference temperature were calculated using the derived equations from Table 1.

2) The suction at temperatures 40F, 45F, 50F, 55F, 60F and 65F were calculated using the derived equation as well.

3) The suction values at these temperatures were replaced in the Grant equation and $\beta_0$ was back-calculated

The resulting $\beta_0$ was logged and the results are shown in Table 2. The calculated $\beta_0$ varied from -290 to -360K. The average $\beta_0$ value was calculated, $\beta_0$ is -305for all types of soils.

Table 2 Back-calculated $\beta_0$ values

| MAAT ($^oK$) | Passing 200 (%) | Plasticity Index | $\beta_o$ ($^oK$) |
|---|---|---|---|
| 277.5 | 20.0 | 0.0 | -294.9 |
| 280.3 | 20.0 | 0.0 | -295.3 |
| 283.1 | 20.0 | 0.0 | -296.0 |
| 285.9 | 20.0 | 0.0 | -296.9 |
| 288.7 | 20.0 | 0.0 | -298.0 |
| 288.7 | 20.0 | 0.0 | -299.3 |
| 277.5 | 20.0 | 2.5 | -294.5 |
| 280.3 | 20.0 | 2.5 | -294.7 |
| 283.1 | 20.0 | 2.5 | -294.5 |
| 285.9 | 20.0 | 2.5 | -294.6 |
| 288.7 | 20.0 | 2.5 | -294.7 |
| 288.7 | 20.0 | 2.5 | -294.7 |
| 277.5 | 20.0 | 7.5 | -299.9 |
| 280.3 | 20.0 | 7.5 | -301.3 |
| 283.1 | 20.0 | 7.5 | -302.9 |
| 285.9 | 20.0 | 7.5 | -304.6 |
| 288.7 | 20.0 | 7.5 | -306.3 |
| 288.7 | 20.0 | 7.5 | -308.2 |
| 277.5 | 30.0 | 0.0 | -294.3 |
| 280.3 | 30.0 | 0.0 | -294.3 |

| MAAT ($^oK$) | Passing 200 (%) | Plasticity Index | $\beta_o$ ($^oK$) |
|---|---|---|---|
| 283.2 | 30.0 | 0.0 | -294.4 |
| 285.9 | 30.0 | 0.0 | -294.7 |
| 288.7 | 30.0 | 0.0 | -295.3 |
| 288.7 | 30.0 | 0.0 | -296.2 |
| 277.6 | 30.0 | 2.5 | -297.3 |
| 280.4 | 30.0 | 2.5 | -298.4 |
| 283.2 | 30.0 | 2.5 | -299.6 |
| 285.9 | 30.0 | 2.5 | -301.0 |
| 288.7 | 30.0 | 2.5 | -302.5 |
| 288.7 | 30.0 | 2.5 | -304.1 |
| 277.6 | 30.0 | 5.0 | -296.3 |
| 280.4 | 30.0 | 5.0 | -297.2 |
| 283.2 | 30.0 | 5.0 | -298.3 |
| 285.9 | 30.0 | 5.0 | -299.5 |
| 288.7 | 30.0 | 5.0 | -300.9 |
| 288.7 | 30.0 | 5.0 | -302.5 |
| 277.6 | 40.0 | 2.5 | -296.0 |
| 280.4 | 40.0 | 2.5 | -296.8 |
| 283.2 | 40.0 | 2.5 | -297.8 |
| 285.9 | 40.0 | 2.5 | -299.0 |
| 288.7 | 40.0 | 2.5 | -300.3 |
| 288.7 | 40.0 | 2.5 | -301.8 |
| 277.6 | 40.0 | 5.0 | -322.9 |
| 280.4 | 40.0 | 5.0 | -326.1 |
| 283.2 | 40.0 | 5.0 | -329.2 |
| 285.9 | 40.0 | 5.0 | -332.4 |
| 288.7 | 40.0 | 5.0 | -335.5 |
| 288.7 | 40.0 | 5.0 | -338.6 |
| 277.6 | 40.0 | 7.5 | -296.9 |
| 280.4 | 40.0 | 7.5 | -297.9 |
| 283.2 | 40.0 | 7.5 | -299.0 |
| 285.9 | 40.0 | 7.5 | -300.4 |
| 288.7 | 40.0 | 7.5 | -301.8 |
| 288.7 | 40.0 | 7.5 | -303.4 |

| MAAT ($^oK$) | Passing 200 (%) | Plasticity Index | $\beta_o$ ($^oK$) |
|---|---|---|---|
| 277.6 | 50.0 | 5.0 | -298.6 |
| 280.4 | 50.0 | 5.0 | -299.9 |
| 283.2 | 50.0 | 5.0 | -301.3 |
| 285.9 | 50.0 | 5.0 | -302.8 |
| 288.7 | 50.0 | 5.0 | -304.4 |
| 288.7 | 50.0 | 5.0 | -306.2 |
| 277.6 | 50.0 | 12.5 | -300.0 |
| 280.4 | 50.0 | 12.5 | -301.4 |
| 283.2 | 50.0 | 12.5 | -303.0 |
| 285.9 | 50.0 | 12.5 | -304.6 |
| 288.7 | 50.0 | 12.5 | -306.4 |
| 288.7 | 50.0 | 12.5 | -308.3 |
| 277.6 | 60.0 | 3.5 | -295.4 |
| 280.4 | 60.0 | 3.5 | -296.1 |
| 283.2 | 60.0 | 3.5 | -296.9 |
| 285.9 | 60.0 | 3.5 | -298.0 |
| 288.7 | 60.0 | 3.5 | -299.2 |
| 288.7 | 60.0 | 3.5 | -300.6 |
| 277.6 | 60.0 | 12.5 | -304.2 |
| 280.4 | 60.0 | 12.5 | -306.0 |
| 283.2 | 60.0 | 12.5 | -308.0 |
| 285.9 | 60.0 | 12.5 | -310.0 |
| 288.7 | 60.0 | 12.5 | -312.0 |
| 288.7 | 60.0 | 12.5 | -314.2 |
| 277.6 | 60.0 | 7.5 | -299.5 |
| 280.4 | 60.0 | 7.5 | -300.9 |
| 283.2 | 60.0 | 7.5 | -302.4 |
| 285.9 | 60.0 | 7.5 | -304.0 |
| 288.7 | 60.0 | 7.5 | -305.7 |
| 288.7 | 60.0 | 7.5 | -307.5 |
| 277.6 | 70.0 | 5.0 | -307.9 |
| 280.4 | 70.0 | 5.0 | -310.1 |
| 283.2 | 70.0 | 5.0 | -312.3 |
| 285.9 | 70.0 | 5.0 | -314.5 |

| MAAT ($^oK$) | Passing 200 (%) | Plasticity Index | $\beta_o$ ($^oK$) |
|---|---|---|---|
| 288.7 | 70.0 | 5.0 | -316.8 |
| 288.7 | 70.0 | 5.0 | -319.2 |
| 277.6 | 70.0 | 10.0 | -340.0 |
| 280.4 | 70.0 | 10.0 | -344.2 |
| 283.2 | 70.0 | 10.0 | -348.4 |
| 285.9 | 70.0 | 10.0 | -352.4 |
| 288.7 | 70.0 | 10.0 | -356.5 |
| 288.7 | 70.0 | 10.0 | -360.4 |
| 277.6 | 80.0 | 7.5 | -295.6 |
| 280.4 | 80.0 | 7.5 | -296.4 |
| 283.2 | 80.0 | 7.5 | -297.3 |
| 285.9 | 80.0 | 7.5 | -298.4 |
| 288.7 | 80.0 | 7.5 | -299.6 |
| 288.7 | 80.0 | 7.5 | -301.1 |
| 277.6 | 80.0 | 10.0 | -295.8 |
| 280.4 | 80.0 | 10.0 | -296.5 |
| 283.2 | 80.0 | 10.0 | -297.5 |
| 285.9 | 80.0 | 10.0 | -298.6 |
| 288.7 | 80.0 | 10.0 | -299.9 |
| 288.7 | 80.0 | 10.0 | -301.0 |

## Summary and conclusions

Data on soils in the NRCS was processed to obtain the MAAT for each sample. Groups of soils with similar properties but different MAAT were grouped and the SWCCs for each group of soils were plotted. A clear inverse relationship between temperature and suction was observed. From visual inspection, the effect of temperature was found to be more discernable at lower degree of saturation levels. Lastly, suction levels for soils with higher PI had notably higher suction values.

Based on the relationship between temperature and suction found for the soils in the database, the results were compared to the suction values define by Grant equation, by using the back-calculation of the $\beta_o$ parameter. It was noticed that even though the temperature effect followed the same trend as the model, it had a slightly more profound effect on suction as that calculated by the Grant equation. The results suggested that the $\beta_0$ value in the Grant equation can be refined by reducing it to -305K from the -350- -450K suggested by Grant (Grant, 2005).

Chapter 5

# STATISTICAL ANALYSIS MODEL

## Suction model using statistical analysis

### *Sample soil selection and procedure*

Statistical analysis was used to provide an accurate suction model and analyze its dependence on temperature as well as PI, and passing200 values. In order to create the database that represents a wide variation in all of these factors, the same database used in chapter 4 comprising of more than 9,000 soils with various PI, passing200, temperatures and suction values was used.  The database did not include the suction value at 20% degree of saturation level needed for this analysis. An Excel® macro was created to determine the suction value for each soil at 20% degree of saturation level. The macro used the goal seek function in Excel® for multiple cells to determine the suction. Soils with missing temperature or suction values were then excluded and the database referenced in appendix A was fed to Minitab®. The cleaned up version of the data base still represented approximately 4,800 soils. The soils locations are presented in Figure 12

Figure 12 Soils distribution map used in the statistical analysis

*Statistical analysis and results*

The data obtained from the NRCS database was processed in Minitab® regression analysis model to obtain the predicted suction equation. The best model found is given by:

$$s = -196 - 29.7\,MAAT + 1483\,PI + 14.65\,Passing200 \qquad [23]$$

Where s is the suction at 20% degree of saturation, MAAT is the mean annual air temperature, PI is the soil plasticity index, and the passing 200 is the percentage of soil passing through sieve number 200.

The screenshot from Minitab is shown in Figure 13. The coefficient of determination (R-square) was found to be 71.4%, which proves that the data points fit the model relatively well. The P value is also an indicator of how statistically significant each factor is in calculating suction. The lower the P value the more statistically significant the factor is. With this in mind the suction value was found to be largely dependent on PI with a P value of 0.00. The next most significant factor was found to be the temperature value and lastly the Passing200.

```
Predictor        Coef   SE Coef       T       P
Constant       -196.2     749.4   -0.26   0.793
temp            -29.7     13.97   -0.71   0.045
PI_01         1482.67     35.81   41.41   0.000
Passing200     14.652     6.370    0.73   0.021


S = 1241.22   R-Sq = 71.4%   R-Sq(adj) = 71.4%


The regression equation is
suction = - 196 - 29.7 temp + 1483 PI_01 + 14.65 Passing200


4848 cases used, 3 cases contain missing values
```

Figure 13 Minitab(R) regression analysis output

*β□ - PI relationship*

The model was used to calculate the β□ values for the whole database. This was done by initially calculating suction at both the reference temperature (70F) and the minimum temperature (30F) using the statistical analysis model. The suction values were then replaced in the Grant equation and the β□ was calculated. Appendix C shows the calculated β□ values. β□ showed strong dependence on PI values. The β□ is linearly inversely proportional to the PI value as illustrated in Figure 14.

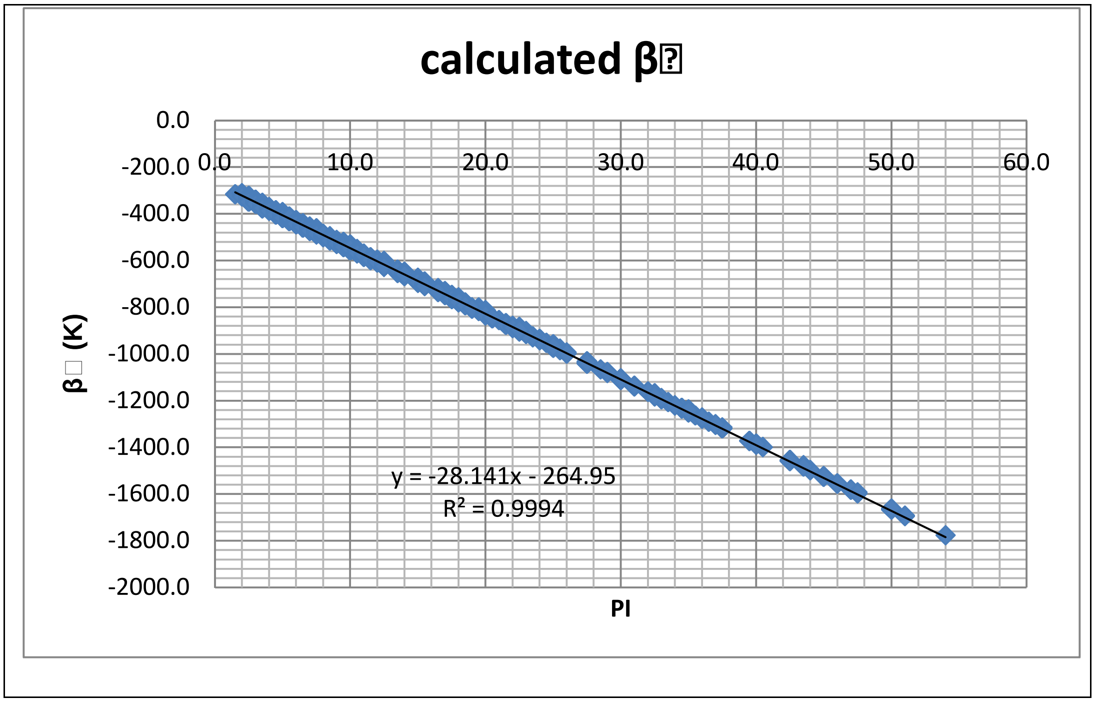


Figure 14 Shows β dependence on PI values

*Suction-PI sensitivity analysis*

Results from the statistical analysis showed that the main influence on suction variation is the difference in the PI value of soil. Suction is noticeably higher for soils with high PI values. This finding was consistent with finding from chapter 4. Figure 15 shows a sensitivity analysis to demonstrate the influence of PI on suction values for a give temperature and passing200 value. The figure illustrates a linear directly proportional relationship between suction and PI.

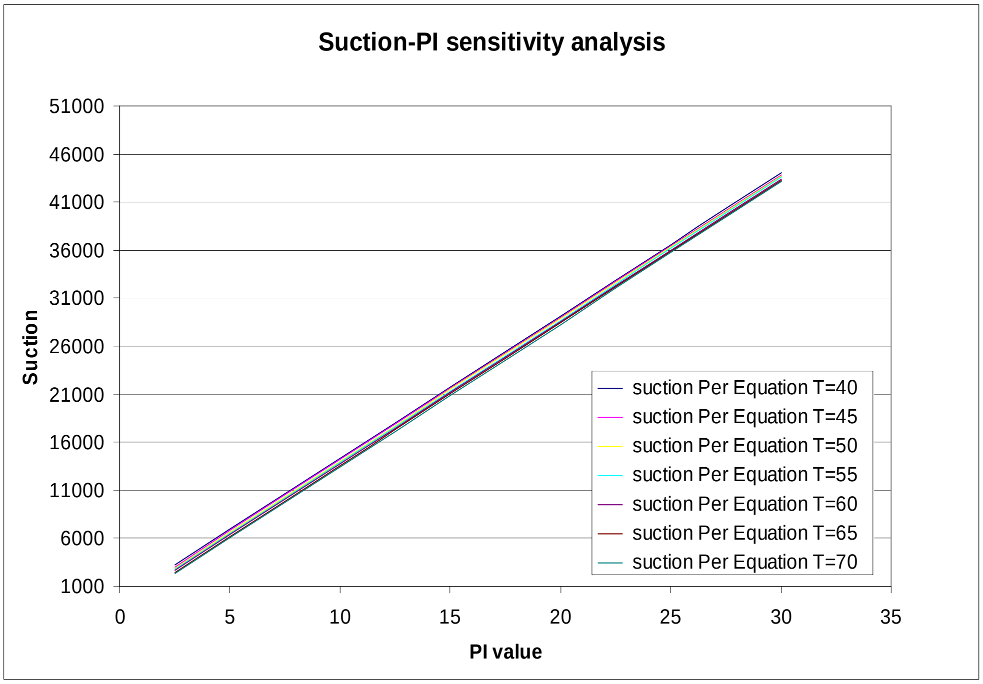


Figure 15 Effect of temperature on suction for different PI values

*Suction_Passing200 Sensitivity Analysis*

Another factor affecting the suction values in soils is the passing200 value. A sensitivity analysis was performed using the equation 23 to isolate the effect of the passing200 value on soil suction. Figure 16 illustrates a directly proportional, linear relationship between passing200 and suction. However, the influence of the passing200 level on soil suction was shown to be much less of that of the PI value.

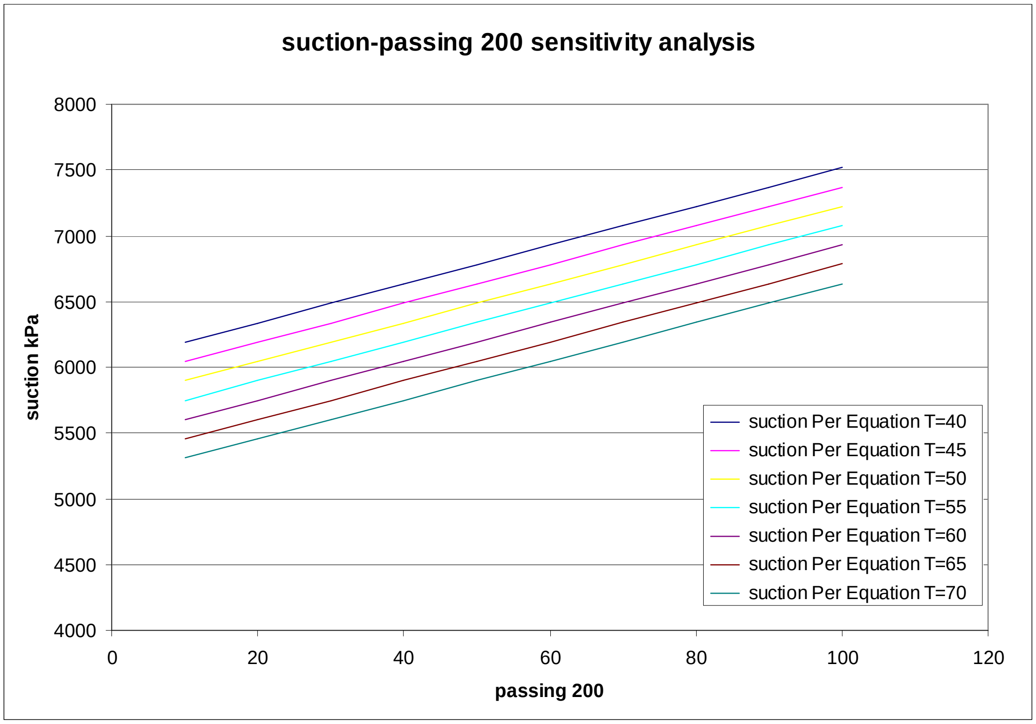


Figure 16 Effect of temperature on suction with different passing 200

*Summary and conclusions*

Results obtained from the statistical analysis on approximately 4,800 soil sample and using Minitab® were in line with the result obtained in chapter 4 using derived equations for each group of soil. This approach was proven to be better not only because of the accuracy of the software used but also because it allowed the created of model that captures the temperature effect along with other important soil properties in the same equation. The analysis showed that the temperature effect on suction is lower than that of soil properties such as the PI value. However, the effect of temperature was large enough not to be ignored.

Chapter 6

# STATISTICAL ANALYSIS MODEL USING TMI

## Introduction to Thornthwaite Moisture Index

The Thornthwaite Moisture Index was found to be the most significant parameter for predicting suction under pavements. In 1948, Thornthwaite introduced the *TMI* as an index that classified the climate of a given location (McKeen and Johnson 1990). The *TMI* quantifies the aridity or humidity of a soil-climate system by summing the effects of annual precipitation, evapotranspiration, storage, deficit and runoff.

The *TMI* values for a region can be estimated from the contour map. For the analysis presented here, the *TMI* value for each sample was obtained from the *TMI* contour map shown in Figure 17 (FHWA-RD-90-033, 1990)

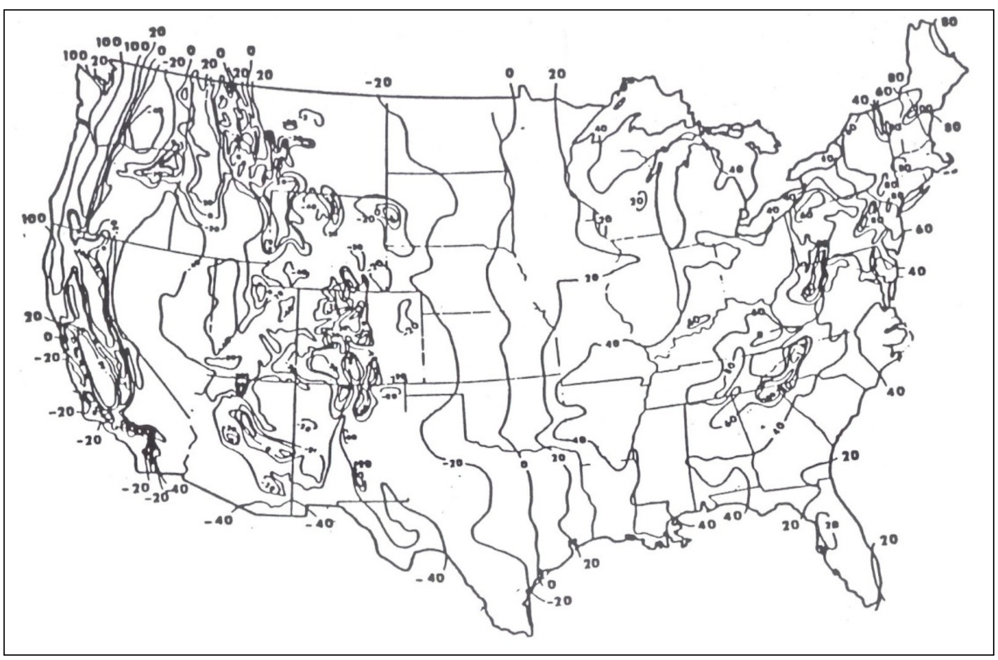

Figure 17 Thornthwaite Moisture Index Contour Map

. The contour map shown in Figure 15 is available only for the continental U.S.A. In order to make the model universal that is for sites within U.S.A., as well as for sites located outside the U.S.A, the NCHRP 1-40D project research team calibrated an equation developed by Thornthwaite in 1948 that estimates the TMI based on climatic parameters and Latitude. The model is called the TMI-ASU model and it is represented by the following equation [24]:

$$TMI = 75\left(\frac{P}{PE} - 1\right) + 10 \qquad [24]$$

Where $TMI$ is the Thornthwaite Moisture Index (dimensionless), $P$ is the annual precipitation (cm), and $PE$ is the adjusted potential evapotranspiration (cm).

<u>Constraints to the model</u>

The monthly heat index, $h_i$, is computer by a power model using the mean monthly air temperature. When negative air temperatures are input into the equation, the output prediction yields an irrational number. The solution recommended by the NCHRP 1-40D to eliminate the problem was to simply let the heat index = 0, whenever a negative mean monthly air temperature was encountered for a given design site.

Previous studies showed soil suction beneath paved areas is governed by the regional TMI and the percentage of fines present in the soil, as the suction increase the TMI value decrease. TMI represents the climatic condition, effect of temperature, precipitation, solar radiation, and the type of soil (Yugantha, 2003).

Minitab Analysis

Another statistical analysis was used to model the effect of TMI along with PI and Passing200 values on the suction level. The database provided in the table below was used to in Minitab® to analyze the TMI effect. The output from Minitab is shown in Figure 18. The output equation from Minitab® was:

S= -6137 - 30.2 passing 200 +964PI + 29.6 TMI……………………….[25]

Where S is the suction, passing 200 is the percentage passing from sieve number 200, PI is the soil plasticity index, and TMI is the Thornthwaite moisture index.

The equation indicated a directly proportional relationship between the suction value and the TMI.

Regression Analysis: Suction versus Passing 200, PI, and TMI

```
The regression equation is
Suction = - 6137 - 30.2 Passing 200 + 964 PI + 29.6 TMI


Predictor       Coef  SE Coef      T      P
Constant       -6137     3439  -1.78  0.086
Passing 200   -30.22    77.67  -0.39  0.700
PI             964.2    182.9   5.27  0.000
TMI            29.62    21.95   1.35  0.189


S = 4114.69   R-Sq = 58.8%   R-Sq(adj) = 54.1%
```

Figure 18 Regression analysis for TMI versus suction

*Summary and conclusion*

The statistical analysis of the influence on TMI on soil suction showed a much less than that of temperature. Difficulties in obtaining the TMI values for a large number of soil samples in the database prevented using an adequate sample size as that used in the temperature effects analysis. Only 28 soils were used in the TMI study which may have affected the accuracy of the analysis as indicated in the R-squared value of 54.1% from Minitab®.

Chapter 7

# CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

## Conclusion with respect to the Grant equation

In recent years the increase in geotechnical engineering applications is becoming wider, especially in the geo-environmental area. As a result, new problems require the extension of current understanding of soil behavior with the description of new phenomena and the incorporation of the environmental variables. The new applications are mainly relate to the effect of temperature change on partially saturated soils. The first technique used to assess the effect of temperature on the soil water characteristic curve included the validation of an existing model making use of a large database. The empirical van Genuchten expression incorporates the effect of temperature on matric potential as described by the following relation:

$$\psi(T) = \psi(T_r)\frac{\beta_0 + T}{\beta_0 + T_r} \qquad [24]$$

Where β□ was proposed to be a constant varying between -350K and -450K for most soils. However, the model did not specify any dependence of β□ on soil properties. This model was validated by using the existing database. Similar soils in different locations all over the United States were gathered in groups of similar soil properties with different mean annual air temperature, or each family of soils the soil water retention curves were plotted at different temperature. For all families plotted there was a clear trend between suction and temperature. The trend was only clear at lower level of degree of saturations, and it is very significant at 20% degree of saturation. The effect of increasing temperature is to decrease the matric potential.  Also using the same approach the β□, a strong dependence of β□ on PI value was observed and modeled. The value of β□ decreased linearly with the increase in PI.

Conclusion with respect to statistical model to incorporate the temperature effect on suction

This approach was followed in order to analyze soils at different locations with the same soil properties and different mean annual air temperature. The soils used in this approach were about 4,800 soils. After calculating the soils suction, Minitab software was used to run the analysis. The analysis provided a clear relation between suction, temperature, soil plasticity index and the percent passing #200 US sieve. A sensitivity analysis on the statistical model obtained indicates that as the temperature decreases the suction increase; and as the PI and passing 200 increase the suction increases.

The model was used to calculate the β values for the whole database. This was done by initially calculating suction at both the reference temperature (70F) and the minimum temperature (30F) using the statistical analysis model. The suction values were then replaced in the Grant equation and the β was calculated. The calculated β values showed strong dependence on PI values. The β is linearly inversely proportional to the PI value

Conclusion with respect to statistical model to incorporate the TMI effect on suction

The statistical analysis of the influence on TMI on soil suction showed a much less than that of temperature. Difficulties in obtaining the TMI values for a large number of soil samples in the database prevented using an adequate sample size as that used in the temperature effects analysis. Only 28 soils were used in the TMI study which may have affected the accuracy of the analysis as indicated in the R-squared value of 54.1% from Minitab®.

Recommendation for future work

The incorporation of the temperature effect in soil retention has not been taking into consideration in the past, but as the increasing trend of geotechnical applications requiring its inclusion continues, a further understanding of the temperature effect on moisture retention is required. The model validated as well as the proposed model in this study show the temperature effect on suction is minimal compared to the soil properties effect, but should not be neglected and should be taking into consideration, especially when applied to barriers for nuclear waste storage and (ET) covers for municipal solid waste containment.

Future research should be done in the laboratory under controlled conditions to validate the findings of this study.

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# APPENDIX A

# SWCC PLOTS FOR SOIL GROUPS WITH SAME CHARACTERISTICS AT DIFFERENT TEMPERATURES

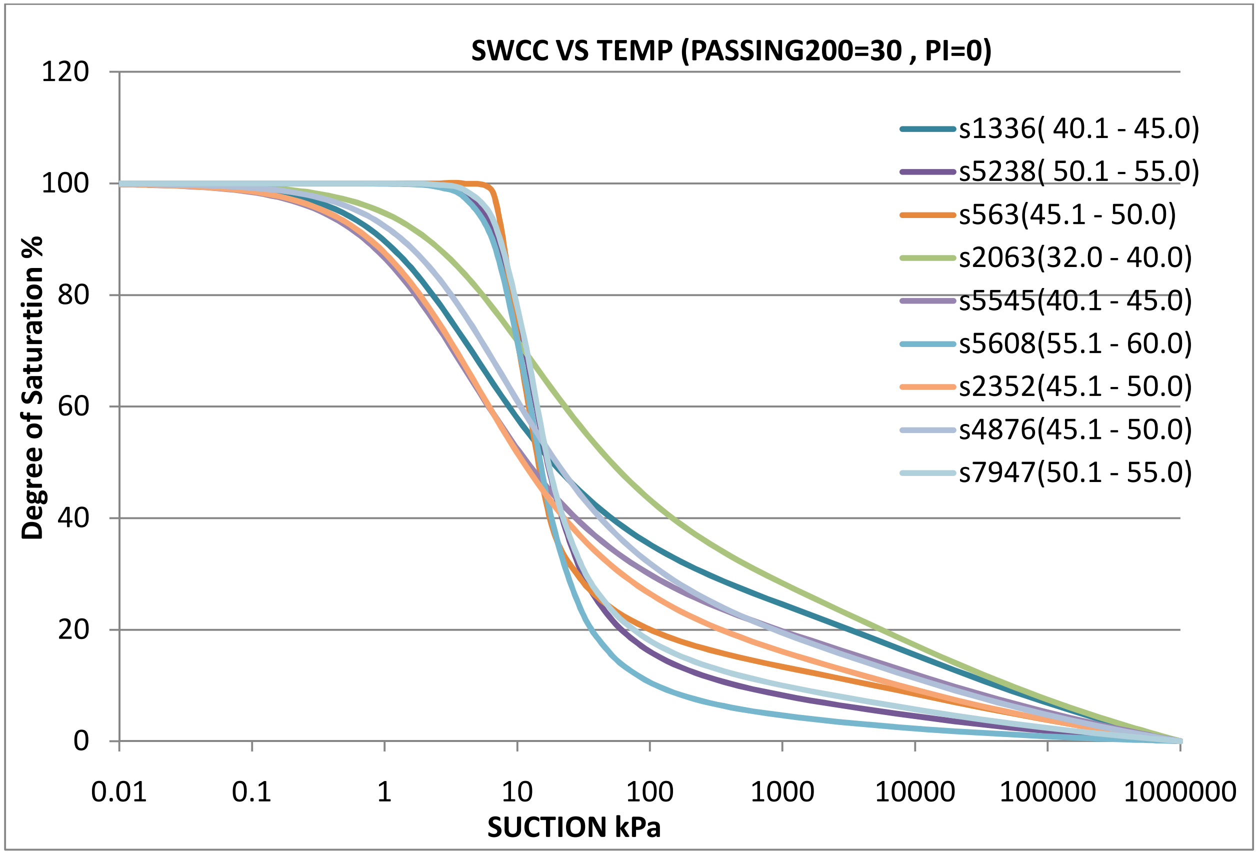



Figure B-1 SWCC for soil family of passing 200=30 and PI=0

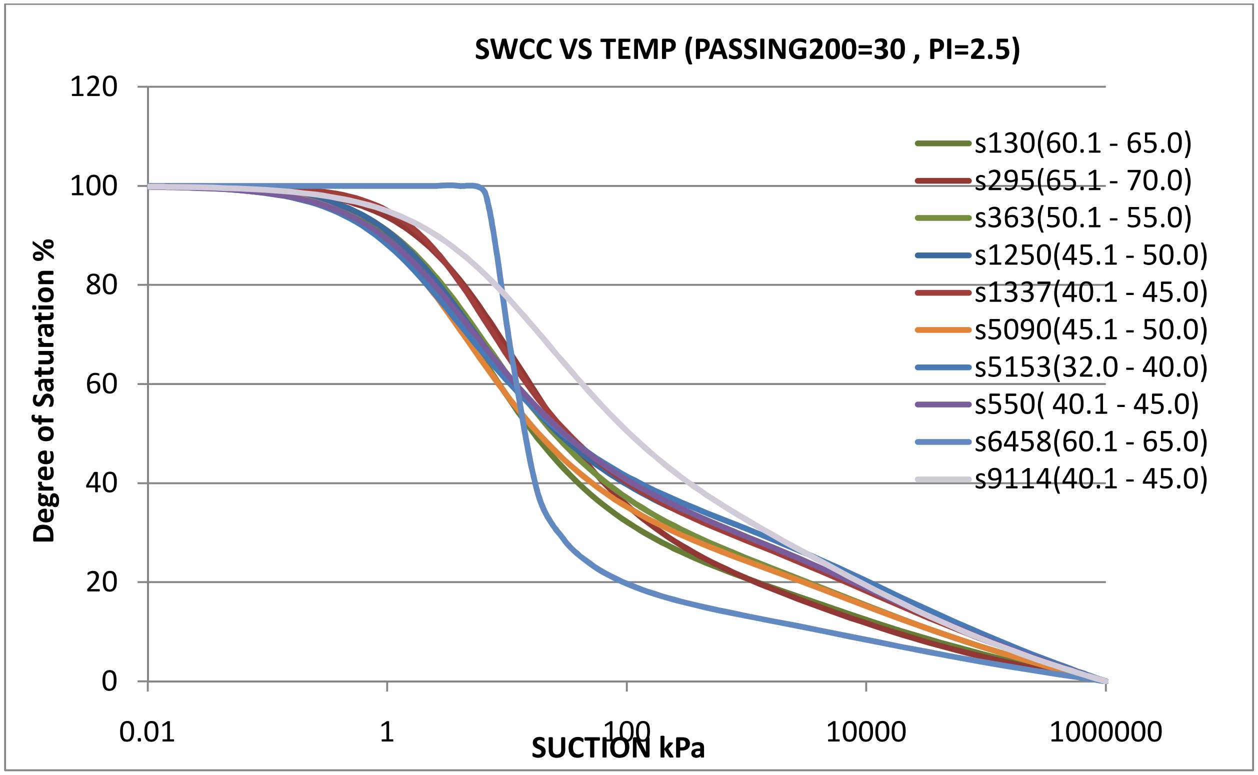



Figure B-2 SWCC for soil family of passing 200=30 and PI=2.5

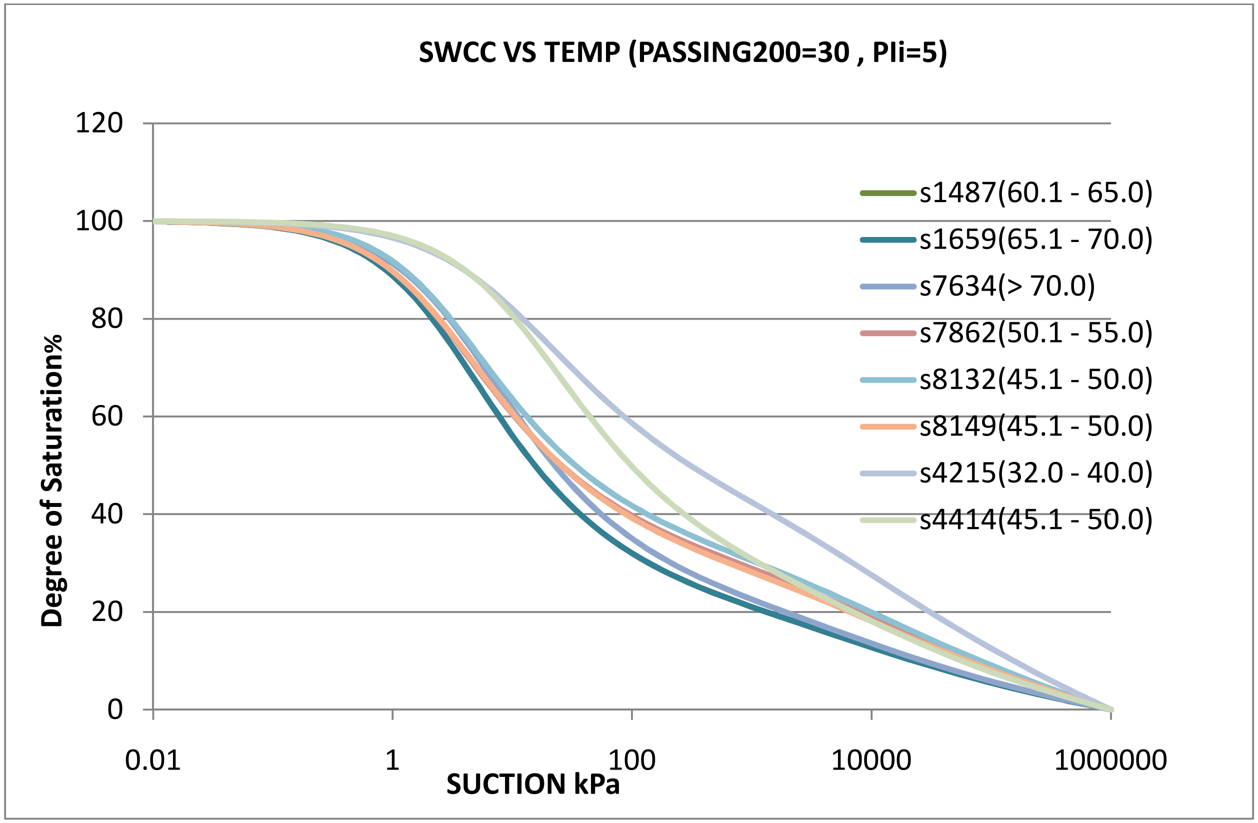



Figure B-3 SWCC for soil family of passing 200=30 and PI=5

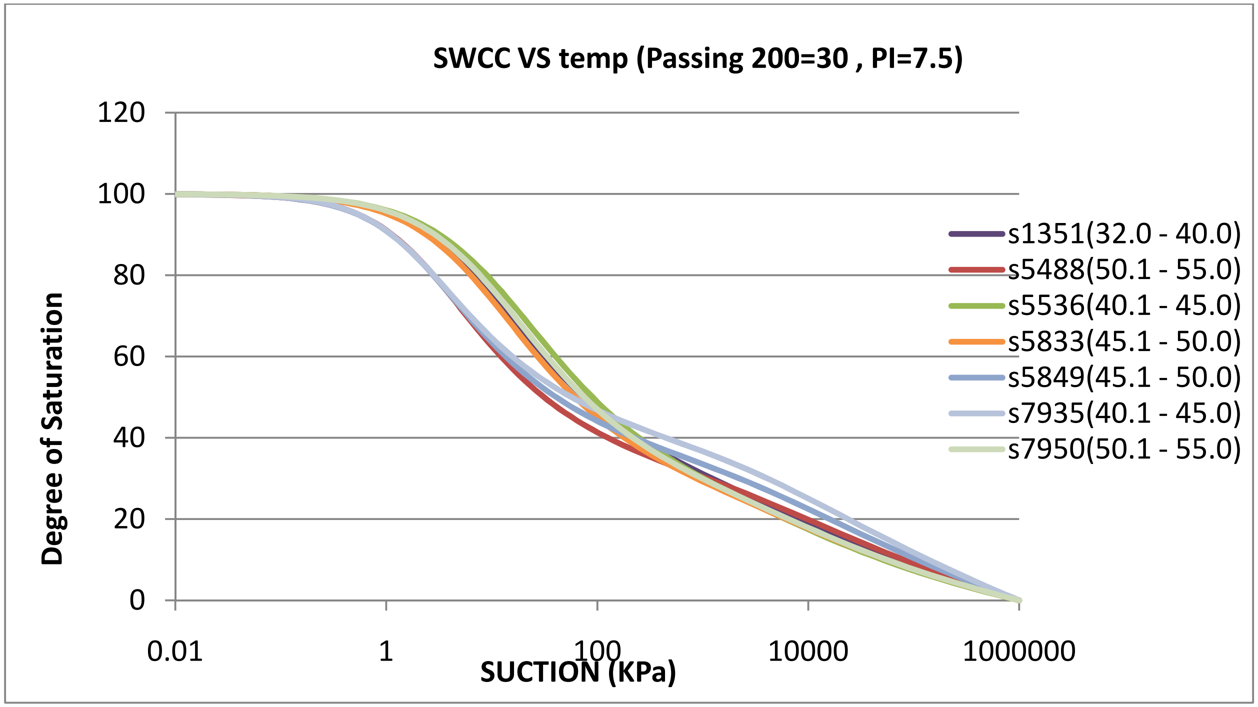



Figure B-4 for soil family of passing 200=30 and PI=7.5

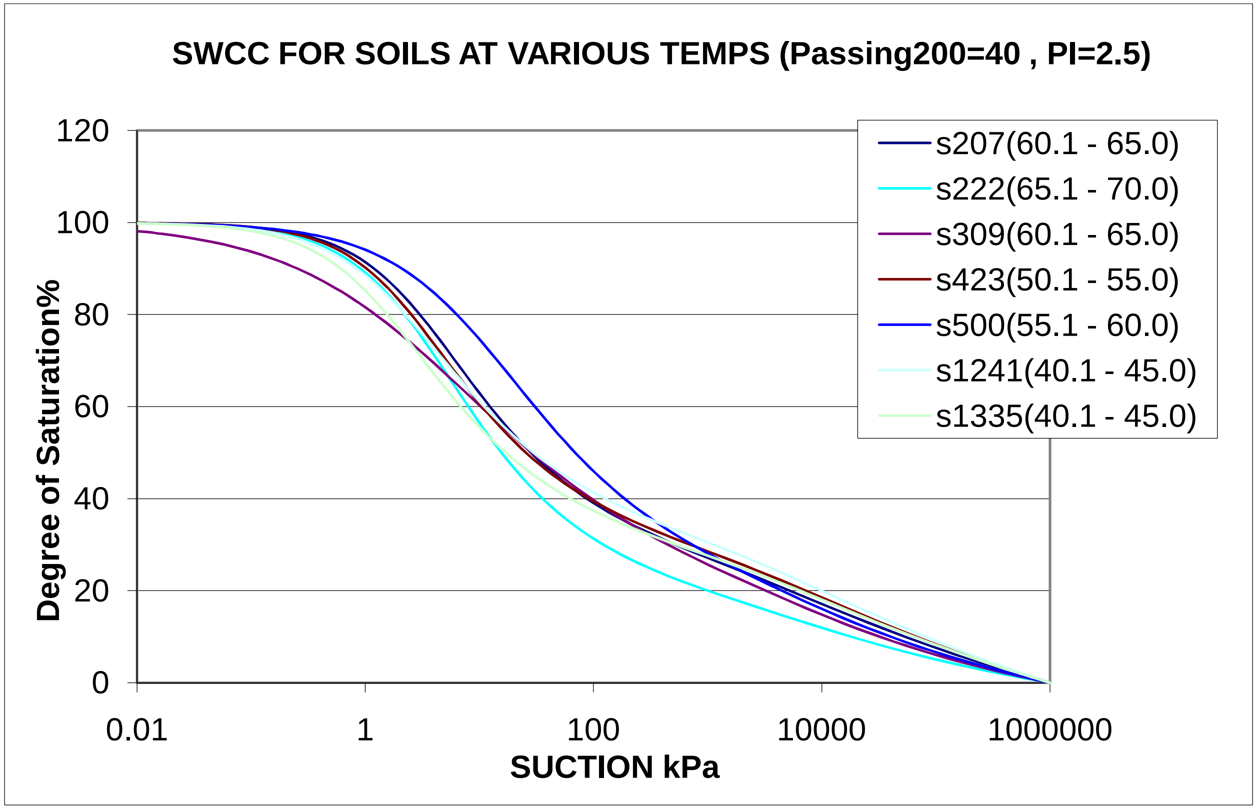



Figure B-5 for soil family of passing 200=40 and PI=2.5

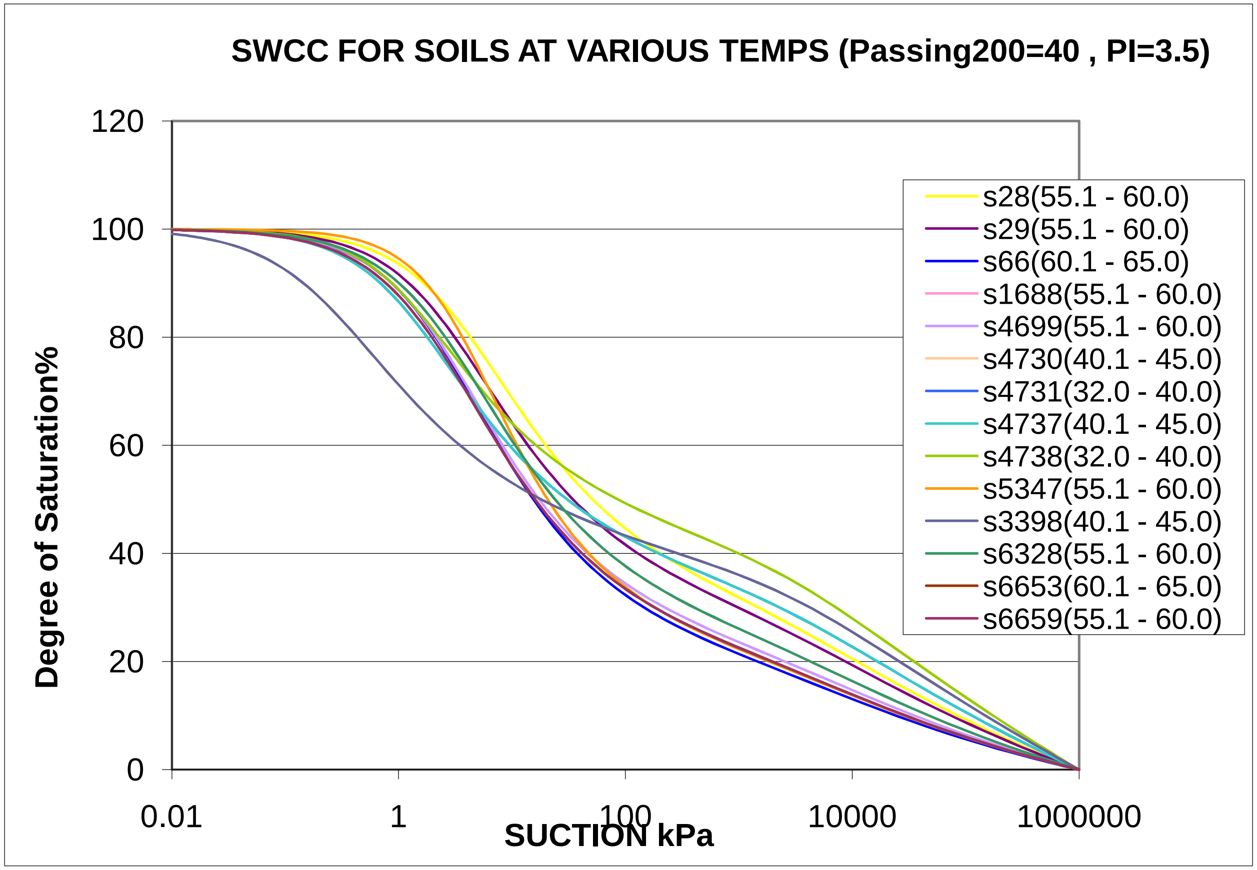



Figure B-6 SWCC for soil family of passing 200=40 and PI=3.5

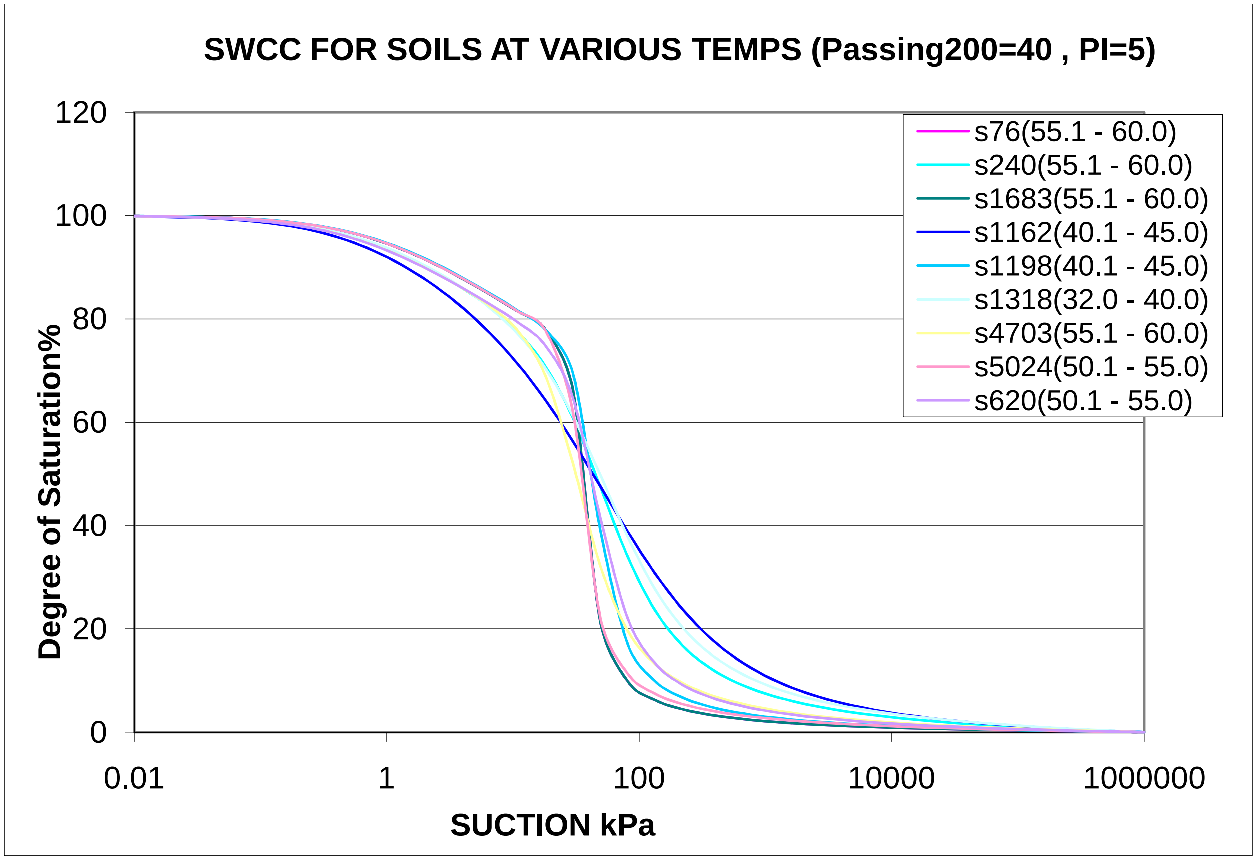



Figure B-7 SWCC for soil family of passing 200=40 and PI=5

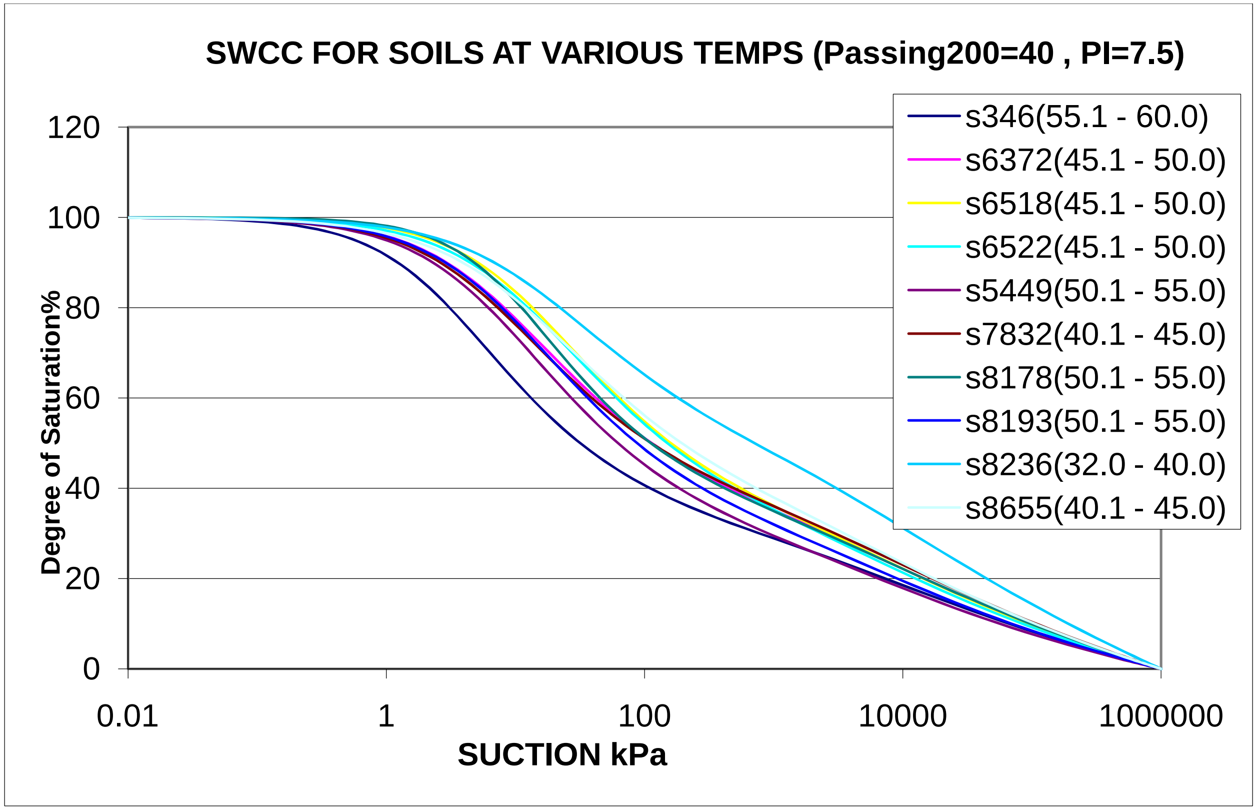



Figure B-8 SWCC for soil family of passing 200=40 and PI=7.5

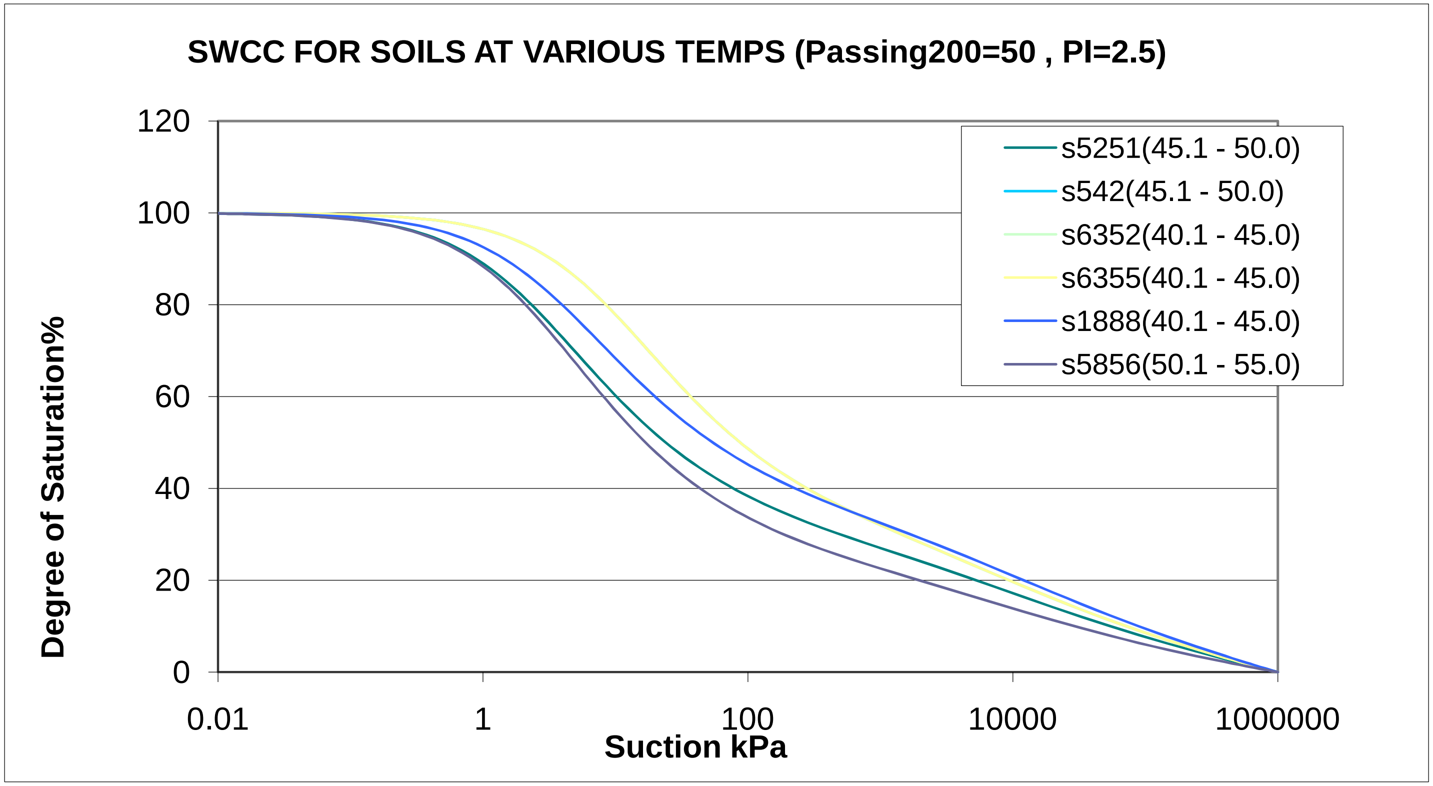



Figure B-9 SWCC for soil family of passing 200=50 and PI=2.5

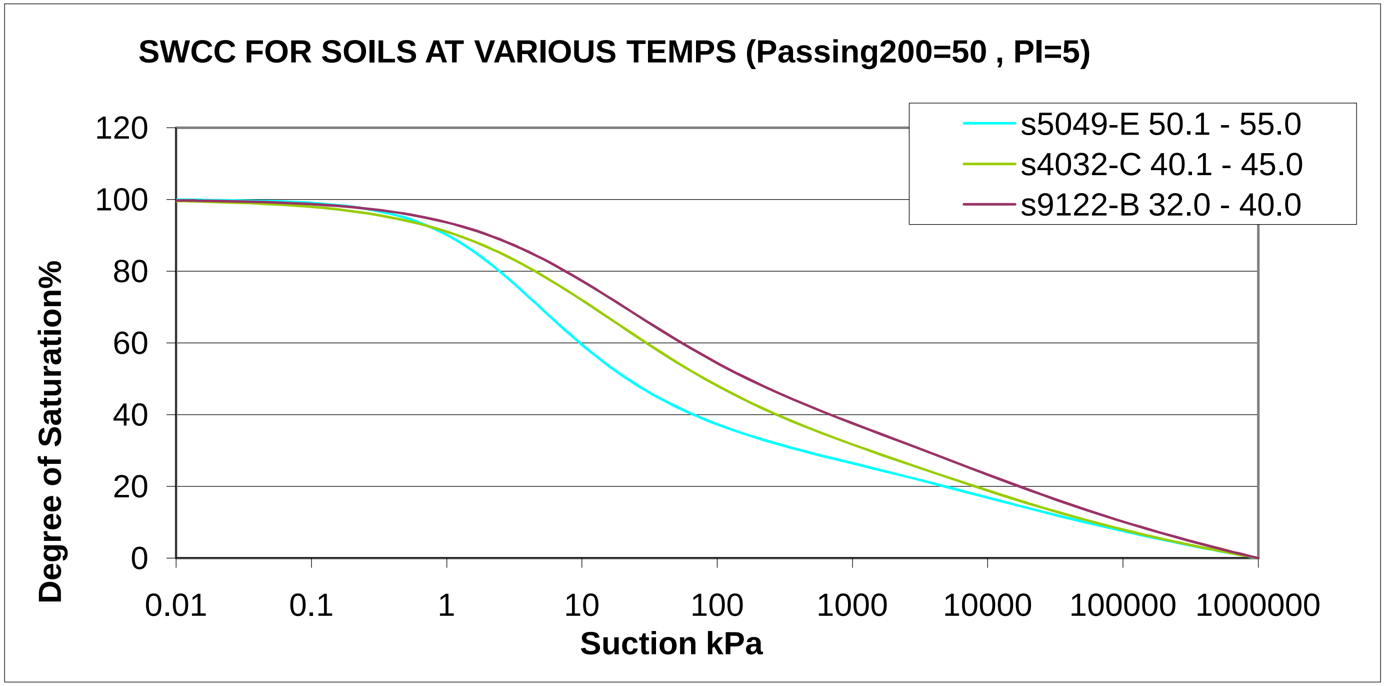
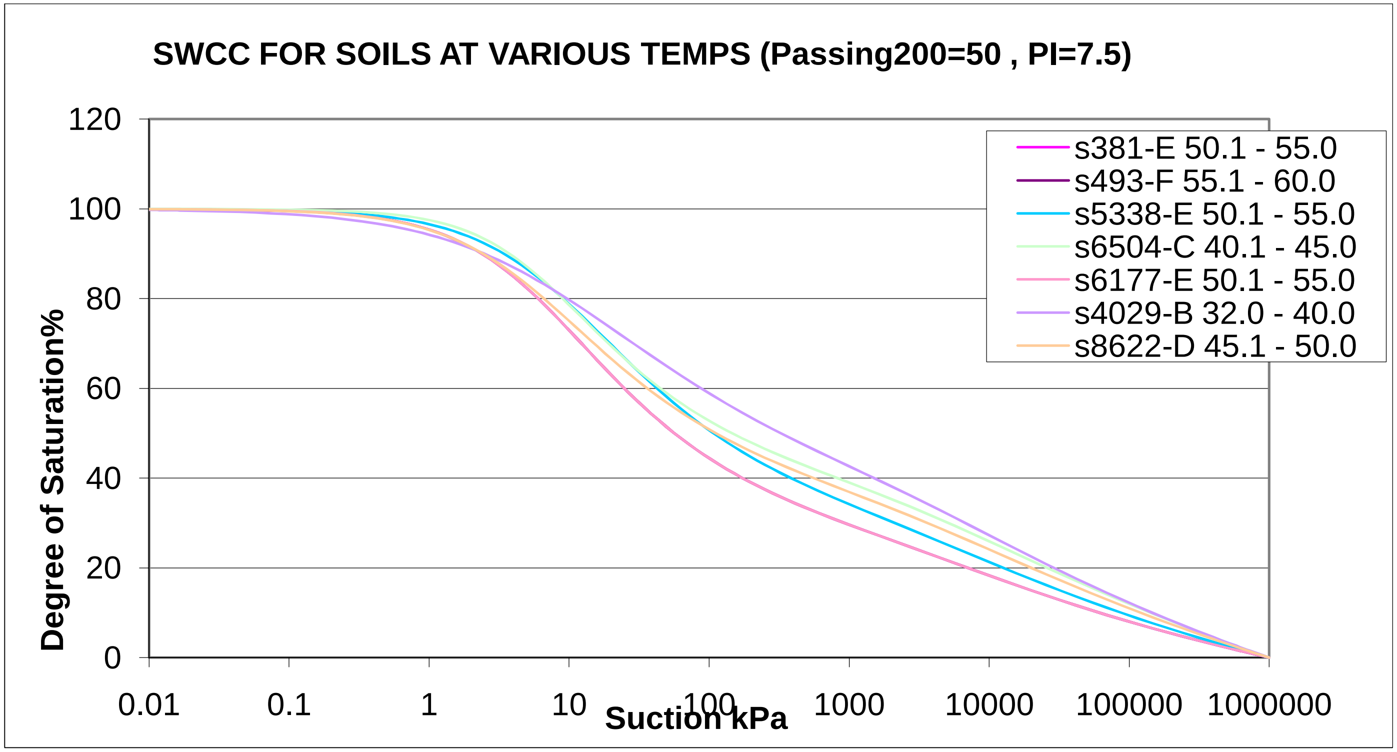



Figure B-10 SWCC for soil family of passing 200=50 and PI=5




FigureB-11 SWCC for soil family of passing 200=50 and PI=7.5

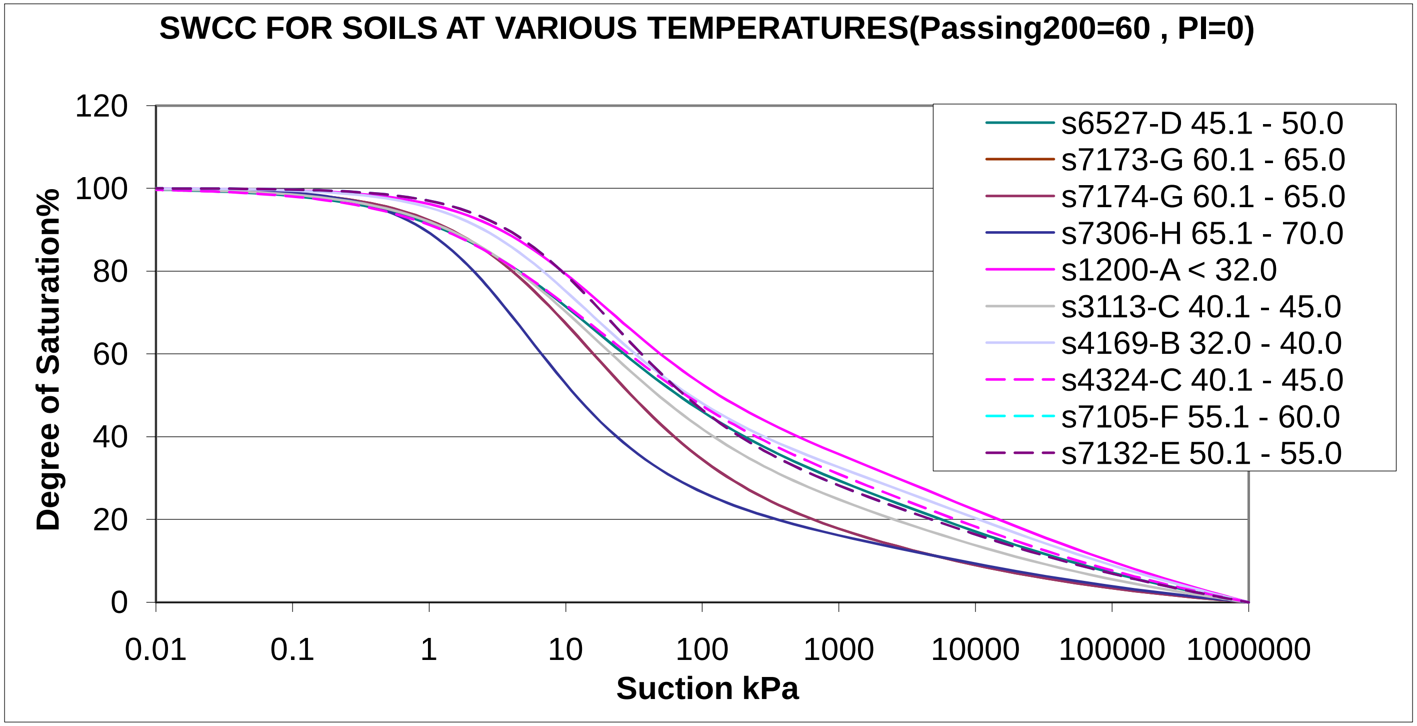



Figure B-12 for soil family of passing 200=60 and PI=0

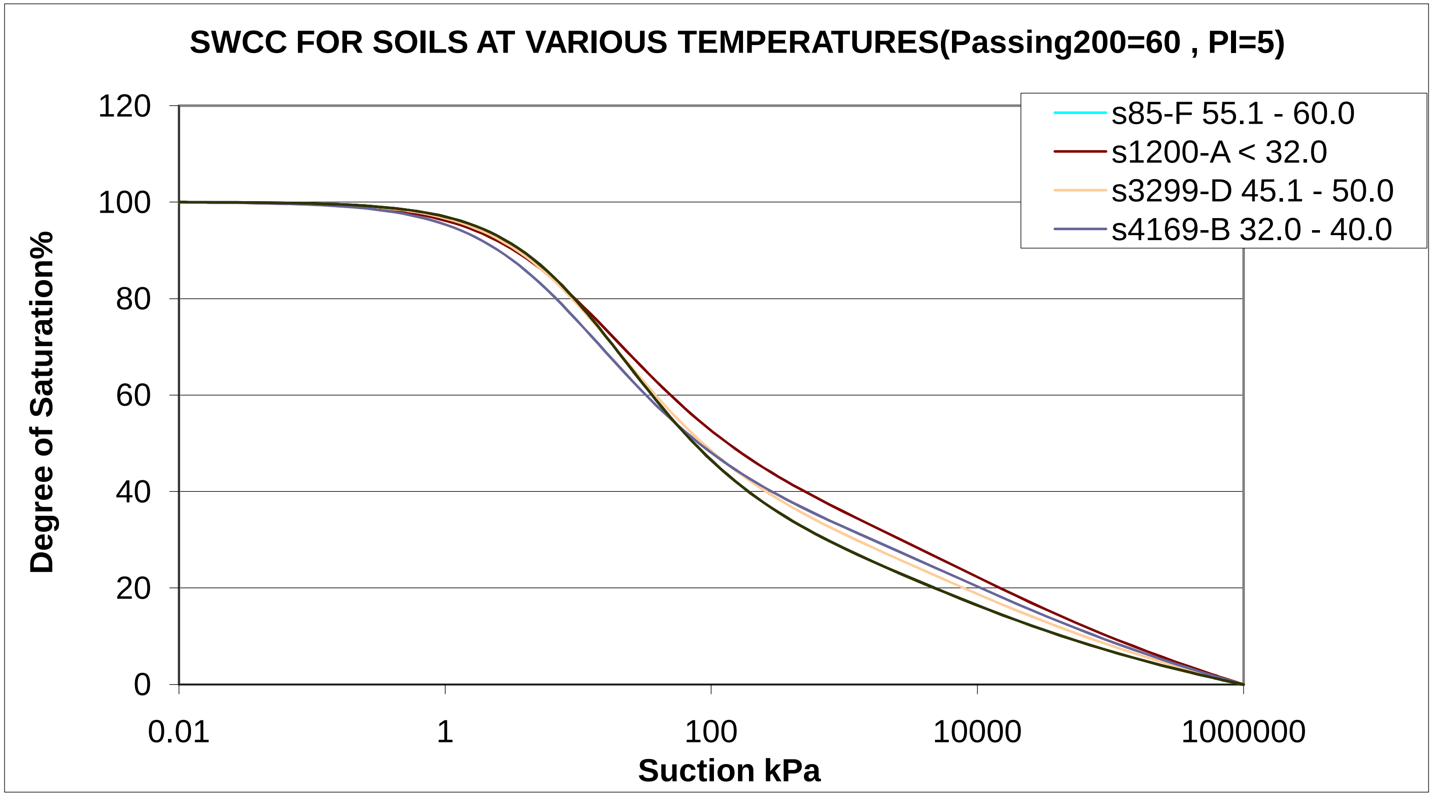



Figure B-13 SWCC for soil family of passing 200=60 and PI=5

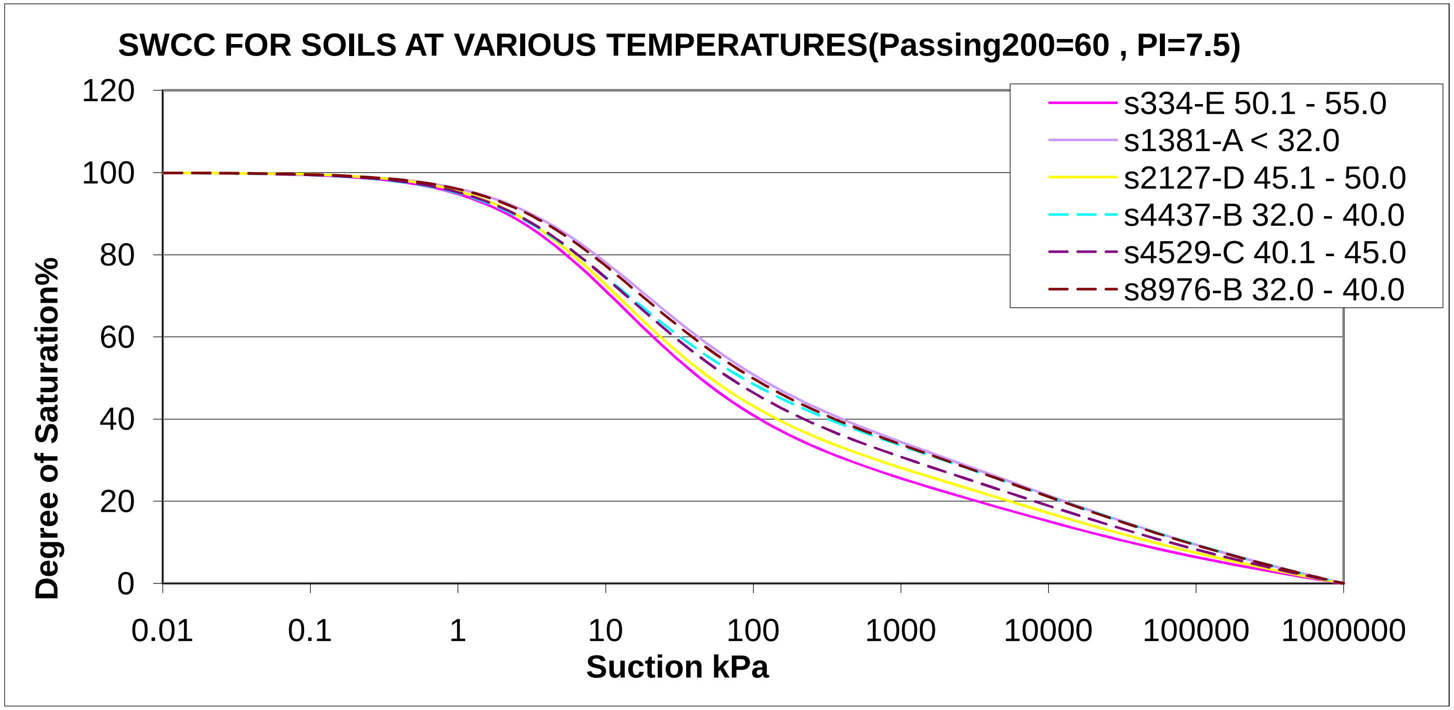



Figure B-14 SWCC for soil family of passing 200=60 and PI=7.5

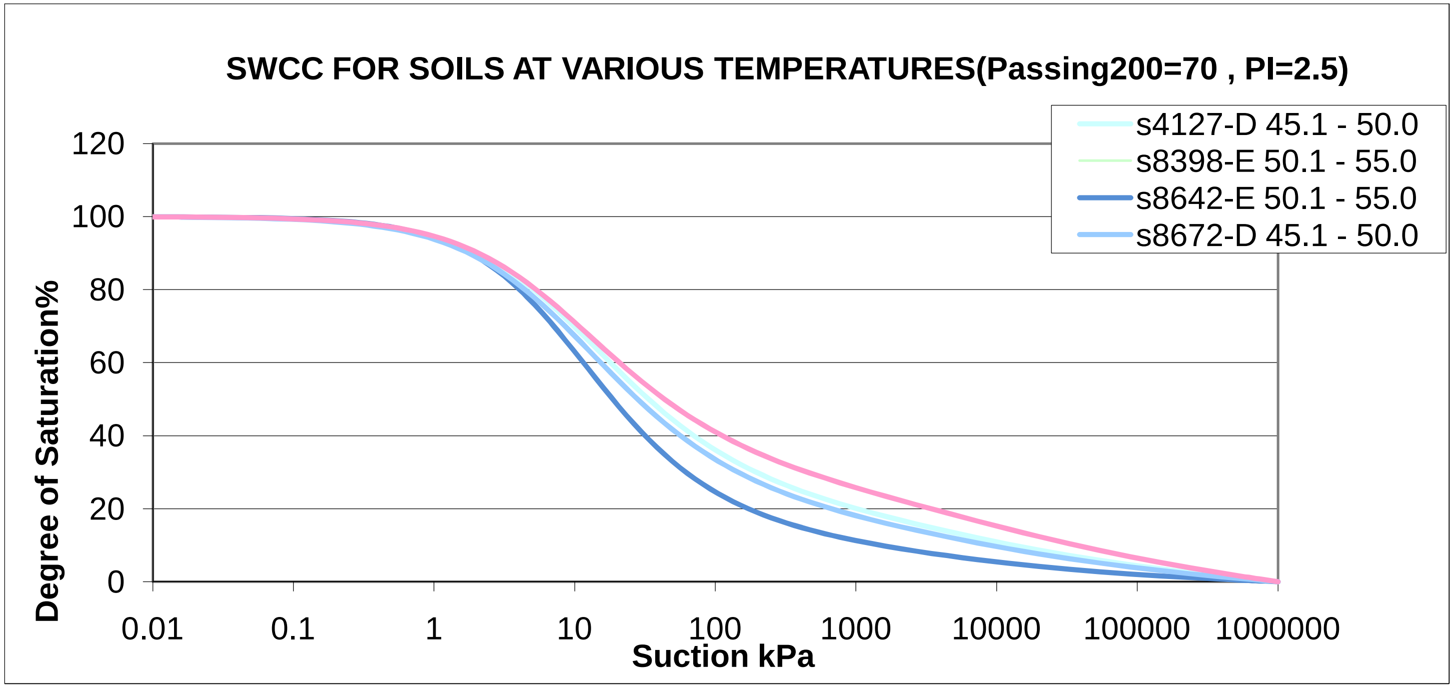



Figure B-15 SWCC for soil family of passing 200=70 and PI=2.5

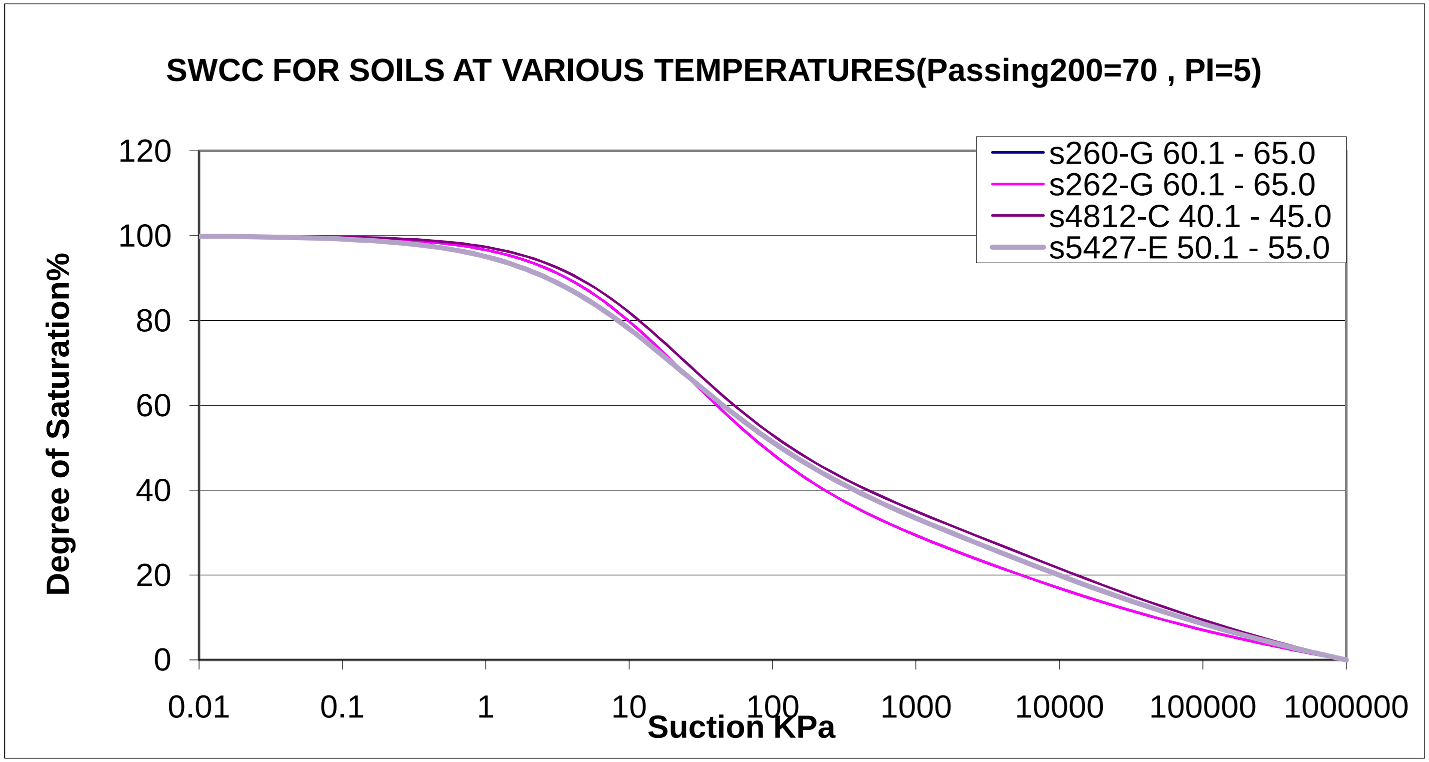



Figure B-16 SWCC for soil family of passing 200=70 and PI=5

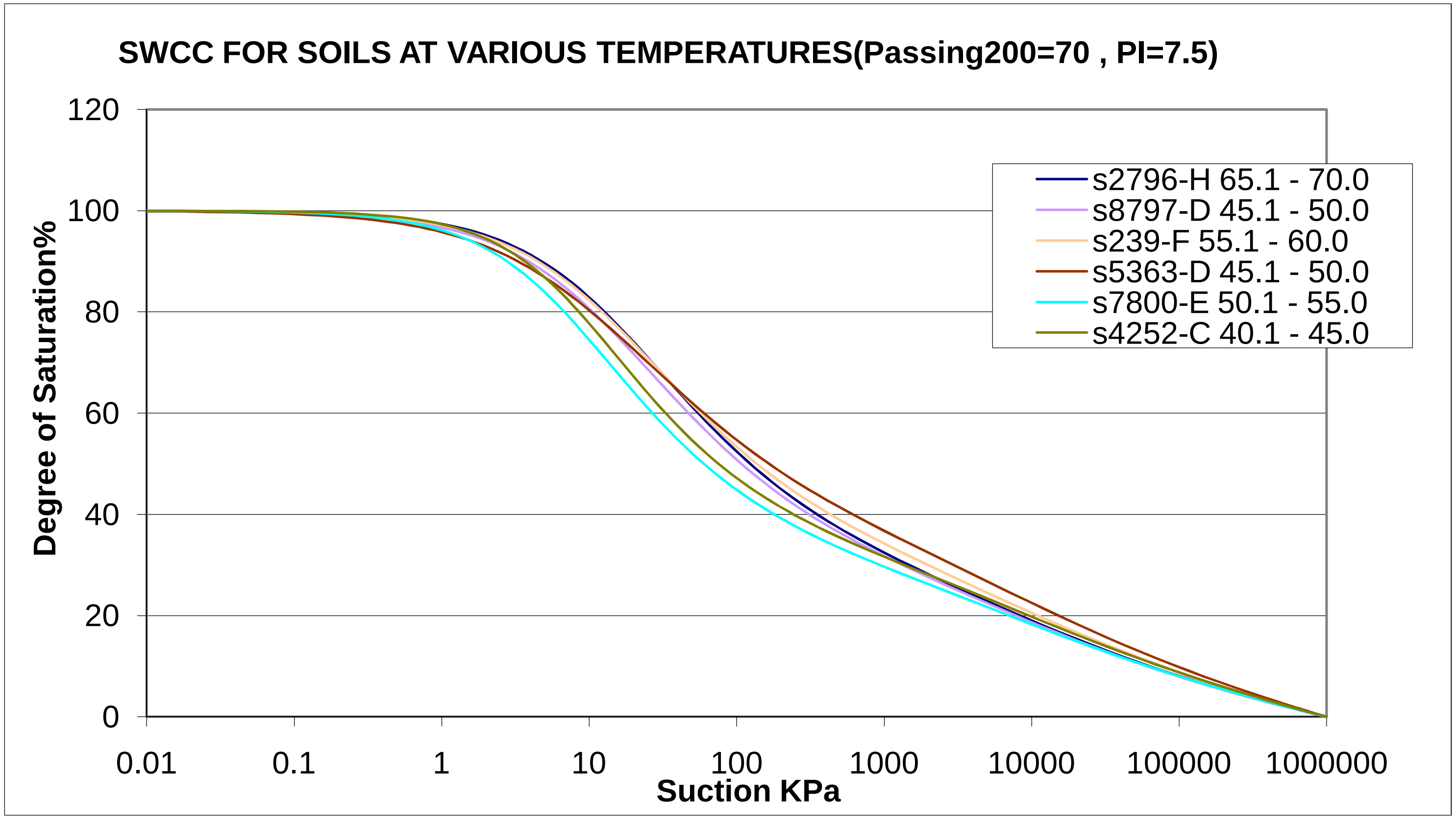



Figure B-17 SWCC for soil family of passing 200=70 and PI=7.5

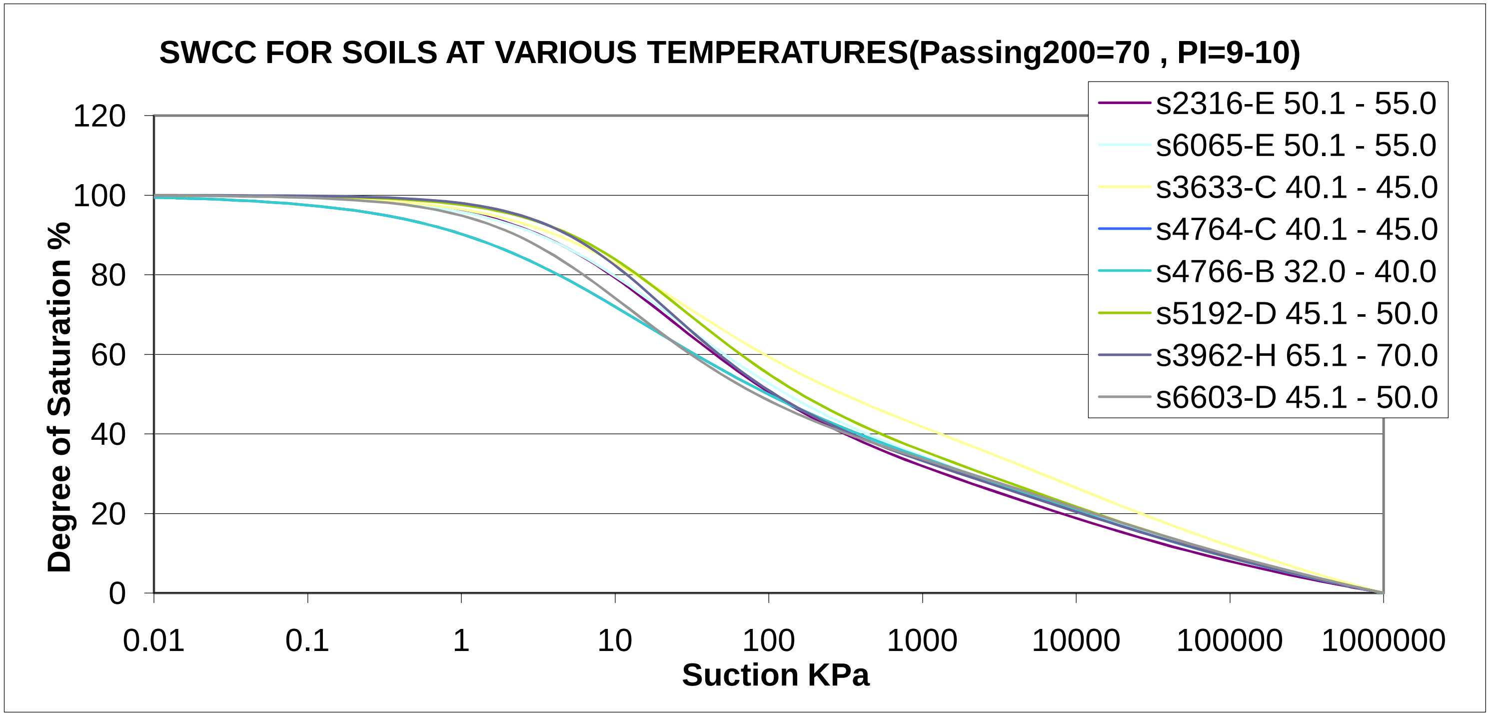



Figure B-18 SWCC for soil family of passing 200=70 and PI=9-10

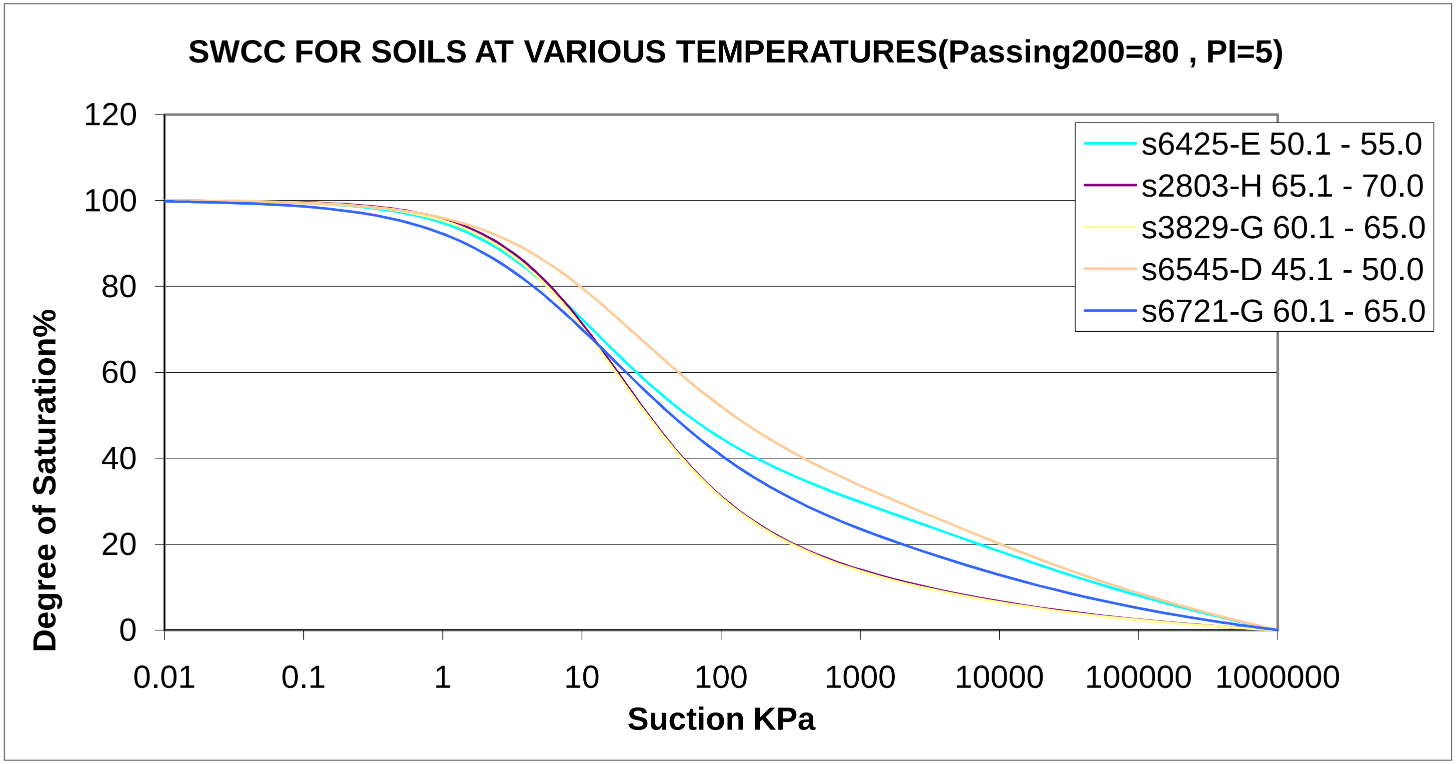



Figure B-19 SWCC for soil family of passing 200=80 and PI=5

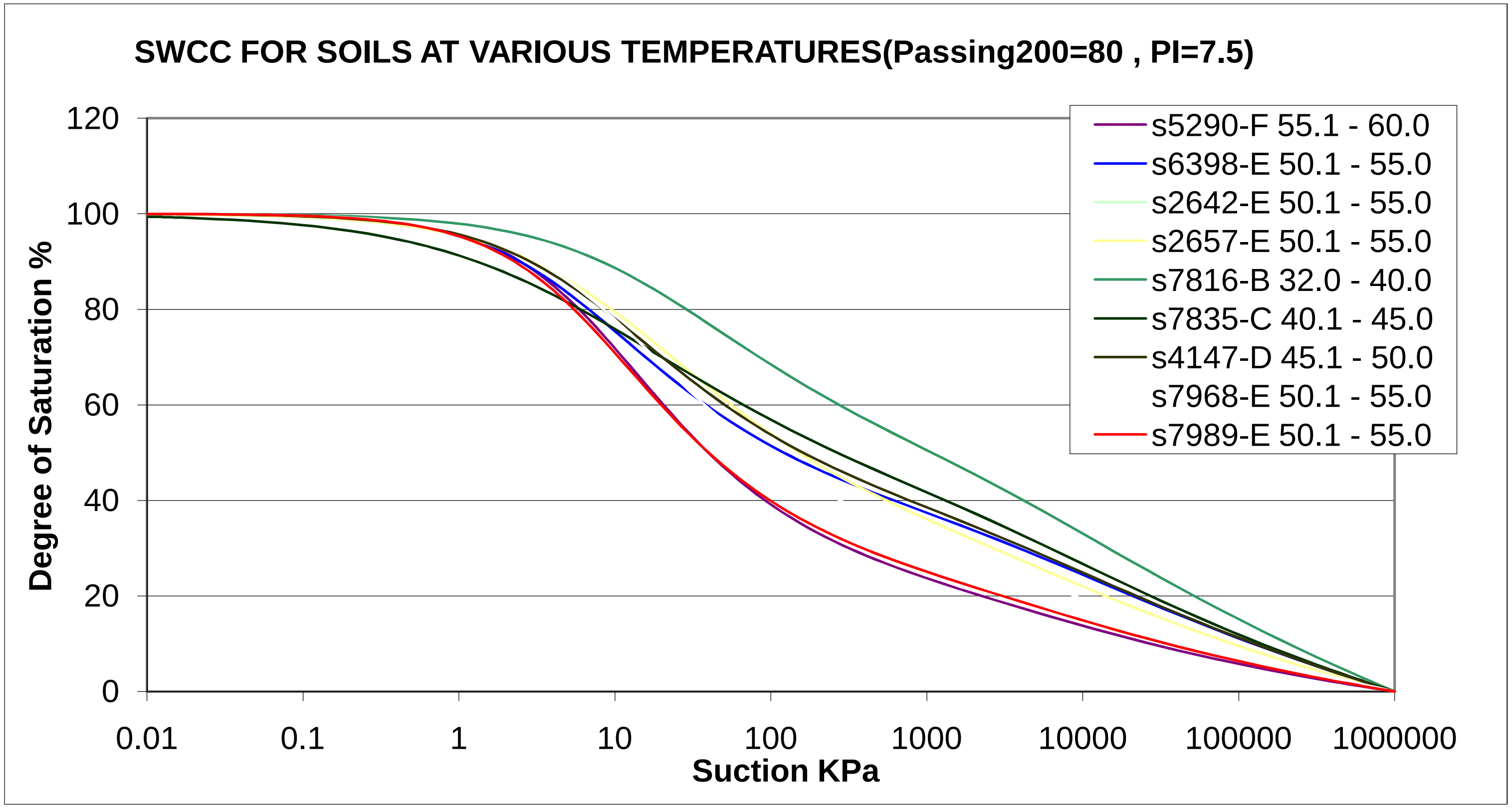



Figure B-20 SWCC for soil family of passing 200=80 and PI=7.5

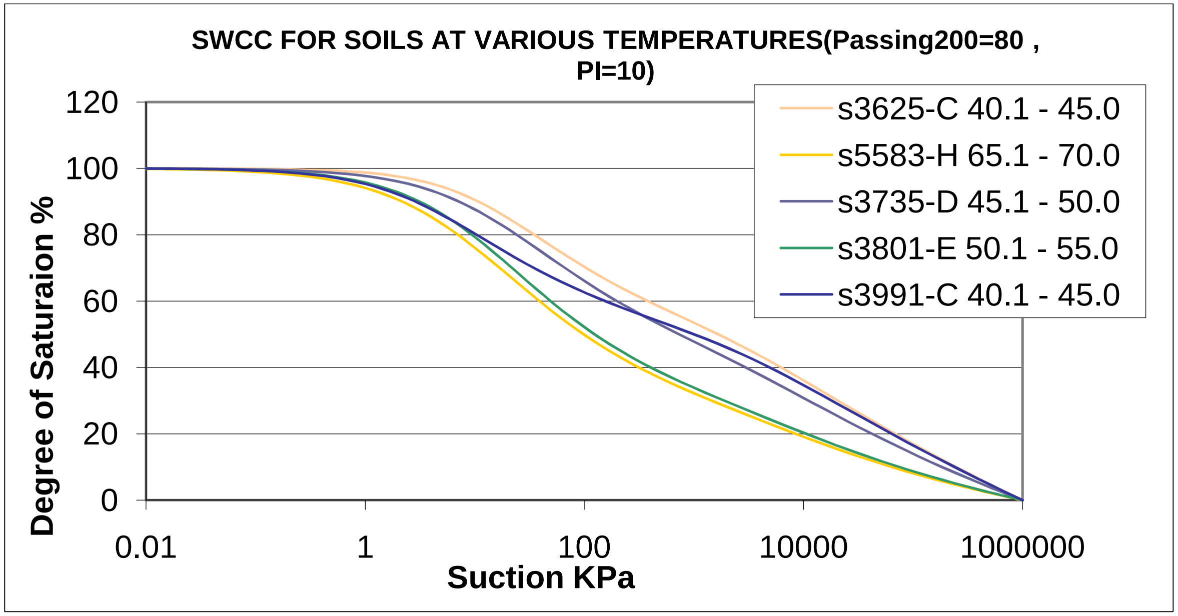



Figure B-21 SWCC for soil family of passing 200=80 and PI=10

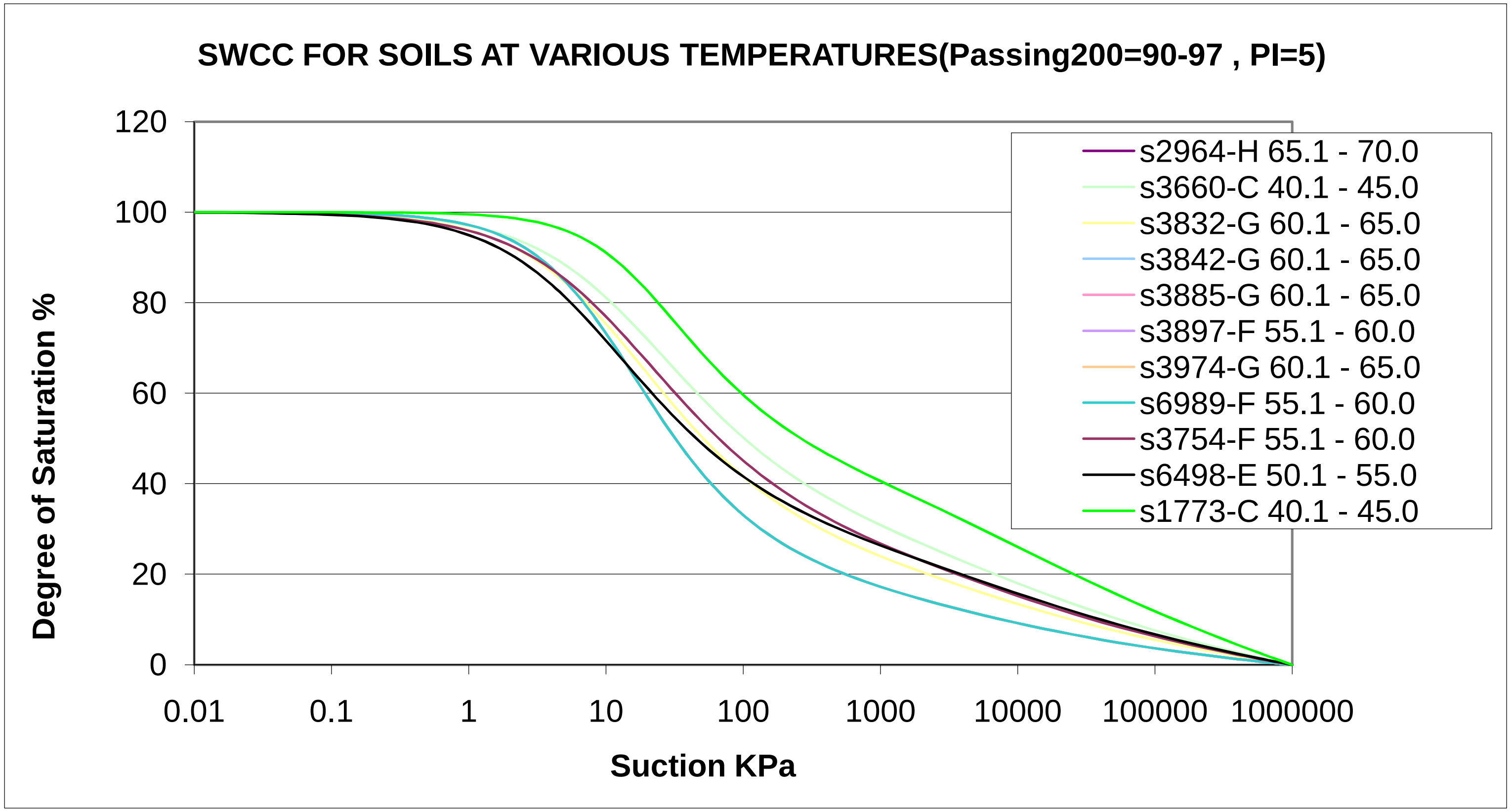



Figure B-22 SWCC for soil family of passing 200=90-97 and PI=5

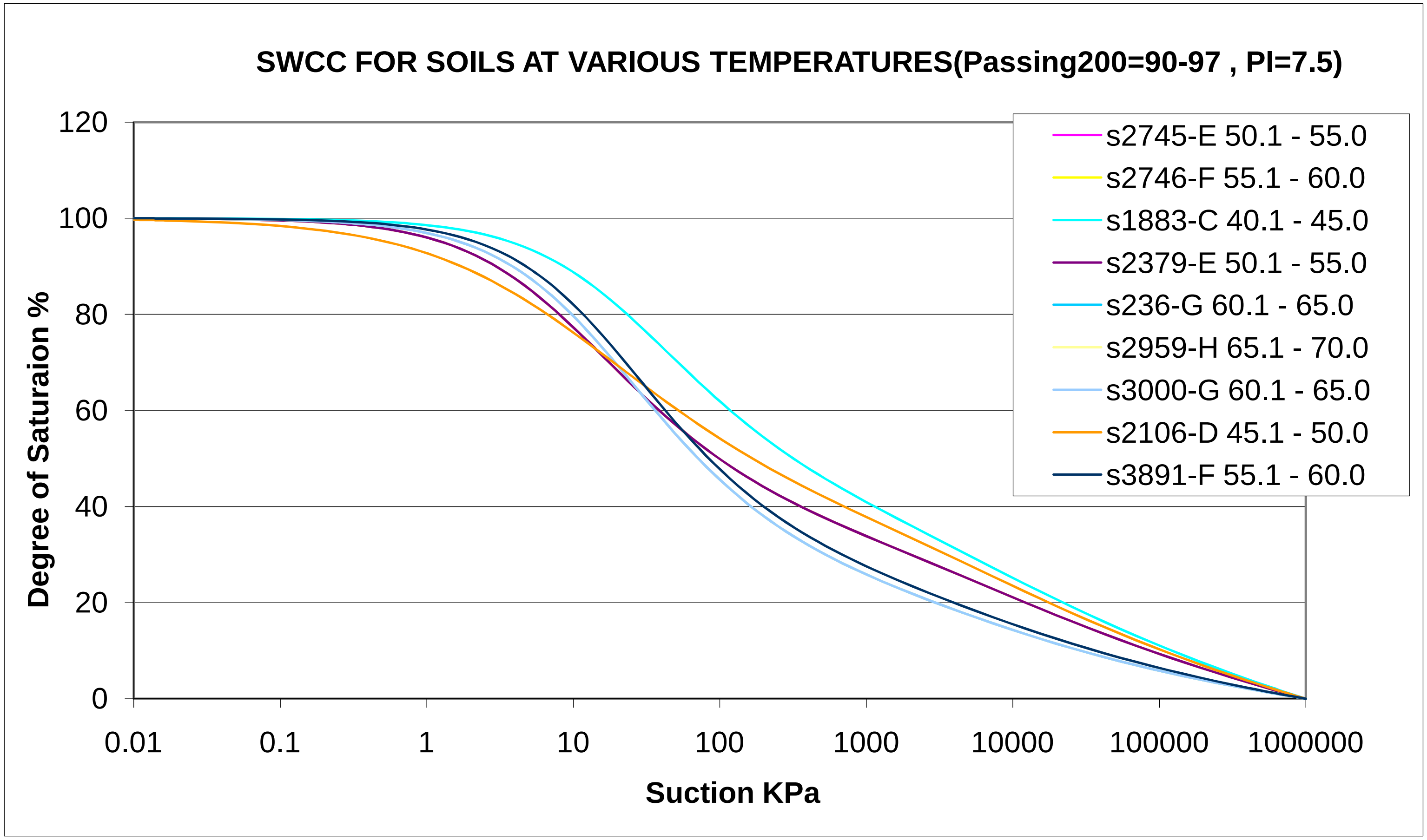



Figure B-23 SWCC for soil family of passing 200=90-97 and PI=7.5

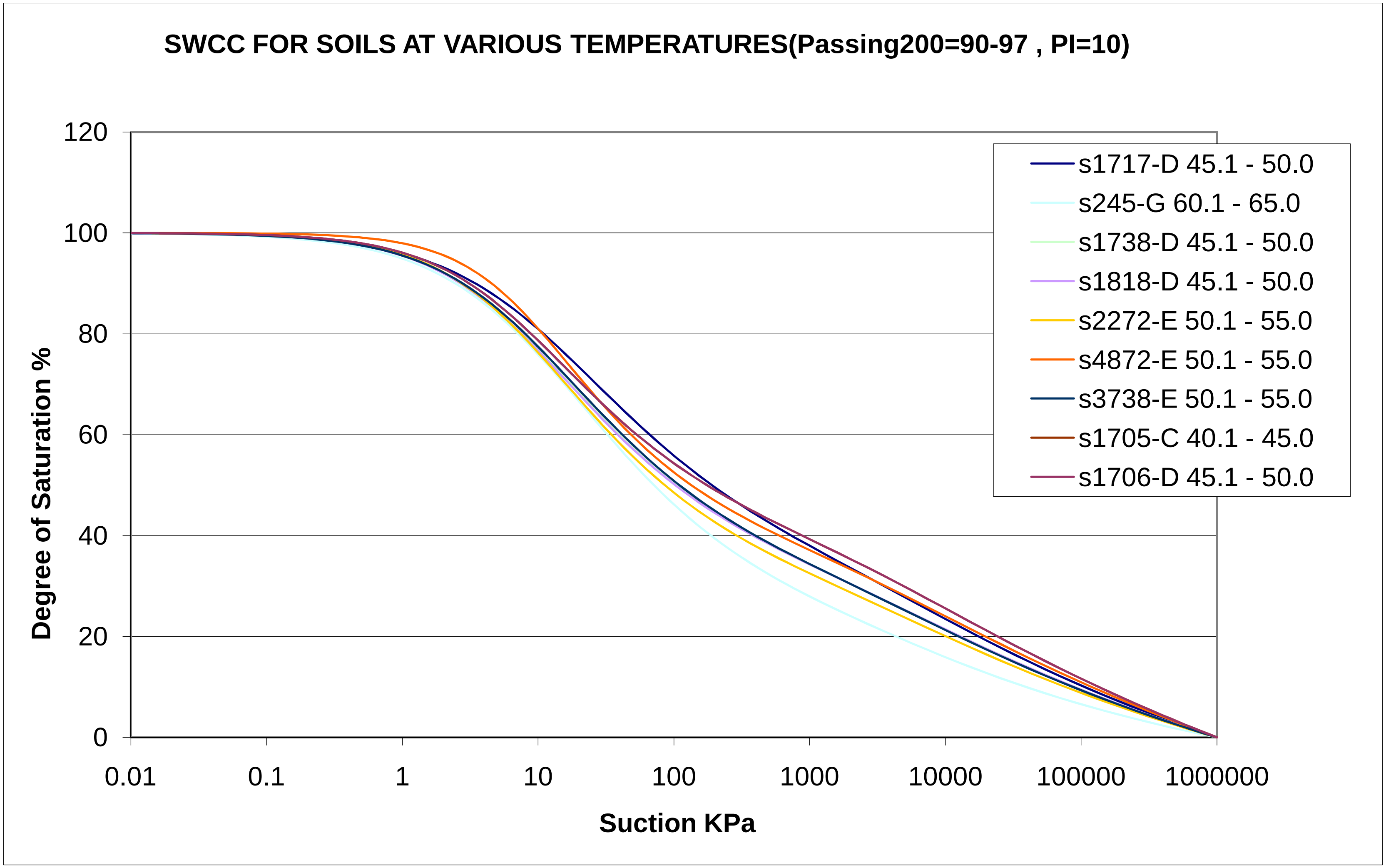



Figure B-24 SWCC for soil family of passing 200=90-97 and PI=10

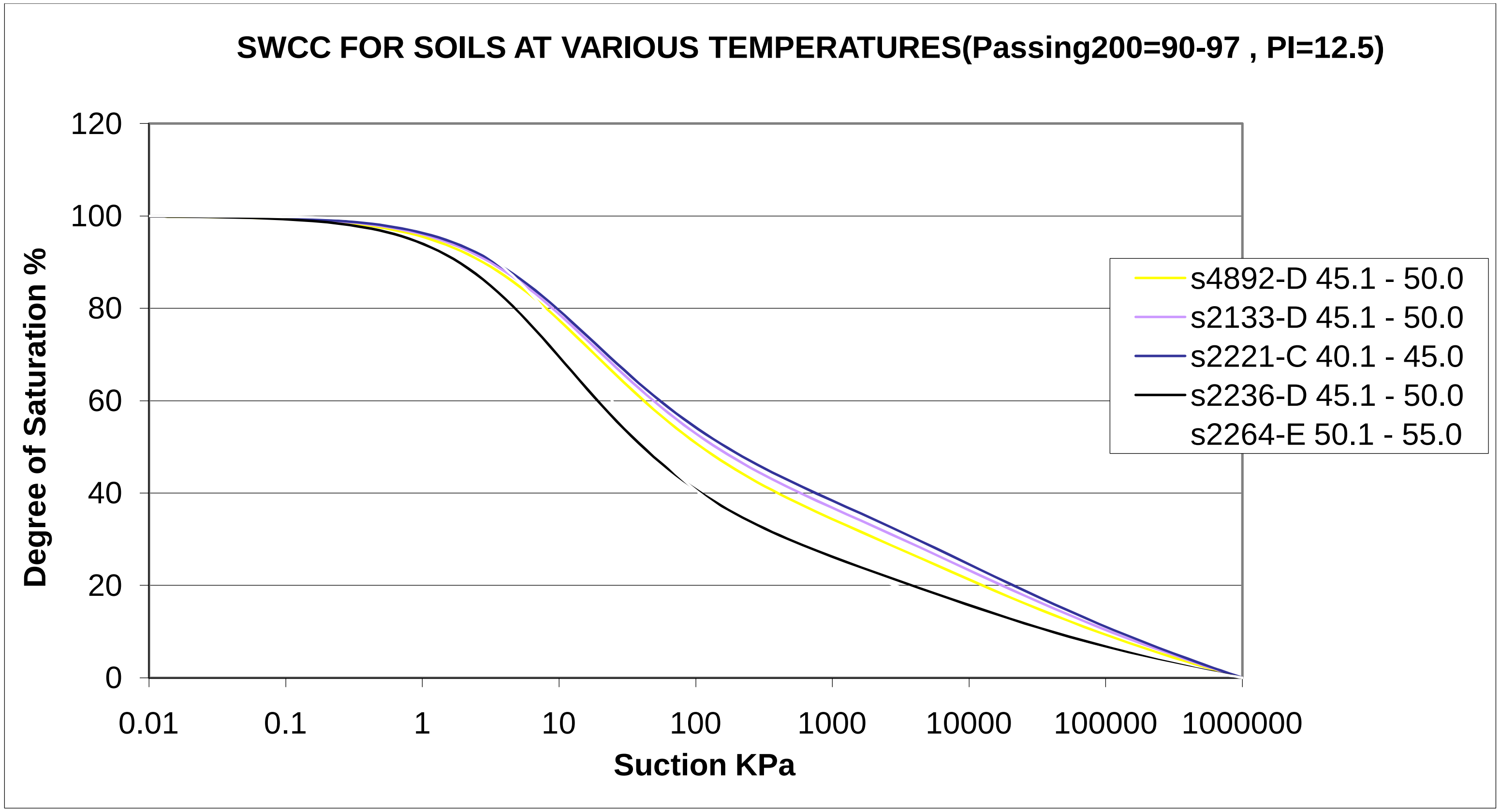



Figure B-25 SWCC for soil family of passing 200=90-97 and PI=12.5

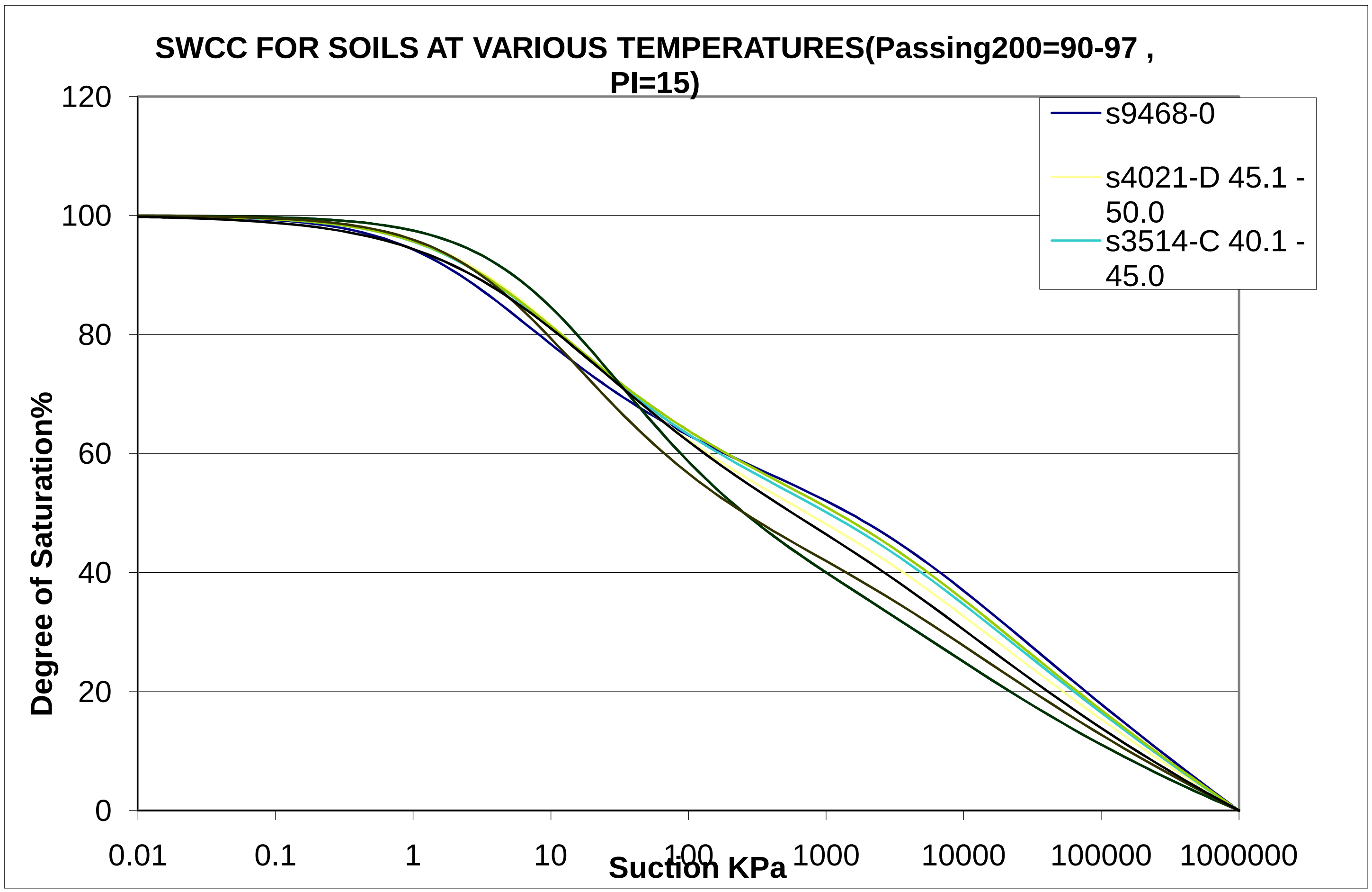



Figure B-26 SWCC for soil family of passing 200=90-97 and PI=15