Prediction of Coefficient of Permeability of Unsaturated Soil

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ABSTRACT

A simple technique is proposed in this paper for estimating the coefficient of permeability of an unsaturated soil based on physical properties of soils that include grain size analysis, degree of saturation or water content, and porosity of the soil. The proposed method requires the soil-water characteristic curve for the prediction of the coefficient of permeability as most of the conventional methods. A procedure is proposed to define the hydraulic conductivity function from the soil water characteristic curve which is measured by the filter paper method. Fitting methods are applied through the program (SoilVision), after indentifying the basic properties of the soil such as Attereberg limits, specific gravity, void ratio, porosity, degree of saturation and wet and dry unit weights.

Keywords: permeability, unsaturated soil, soil water characteristic curve, filter paper.

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الخلاصة

تم توظيف طريقة بسيطة لتقدير معامل النفاذية للترب غير المشبعة بالاعتماد على الخصائص الفيزيائية للترب والتي تتضمن التدرج الحبيبي ودرجة التشبع او المحتوى المائي والمسامية للتربة. هذه الطريقة تحتاج الى ايجاد منحني خصائص الرطوبة للتربة لايجاد معامل النفاذية حيث تعتبر خطوة ضرورية لايجاد معامل النفاذية. في هذا البحث تم استخدام طريقة بسيطة واقتصادية لايجاد منحني الرطوبة وذلك باستخدام طريقة ورقة الترشيح. بعد ان تم ايجاد منحني خصائص الرطوبة، استخدم برنامج (Soil Vision) بعد تعريف الخصائص الاساسية مثل حدود اتربرك والوزن النوعي و درجة التشبع والكثافة الرطبة والجاف.

الكلمات المفتاحية: النفاذية، الترب غير المشبعة، منحني خصائص التربة، ورقة الترشيح.

1.INTRODUCTION

In seepage analysis of unsaturated soil, the coefficient of permeability is an important parameter because many field problems are analyzed on the basis of soil permeability. Various measuring techniques have been developed in the laboratory and in the field to evaluate the unsaturated coefficient of permeability, **Fredlund and Rahardjo, 1993.** The direct measurement of coefficient of permeability of unsaturated soil can be tedious, time-consuming, and expensive. Furthermore, the accuracy of some testing results is often relatively poor, and the number of measurements required to adequately characterize an area can rapidly become prohibitive, as soil properties often show large in situ variability **Mbonimpa, 2006.** For these reasons, it is more convenient to have a practical method for estimating the expected hydraulic properties and to assess how these values may be influenced by changing conditions. The coefficient of permeability of unsaturated soil is not a constant like one of saturated soil. It can vary widely with the variation of the moisture content of soil. The relationship between water content and matric suction is called soil–water characteristic curve. Therefore, the coefficient of permeability is often represented by the function of matric suction. Commonly, the coefficient of permeability of unsaturated soil is predicted using the soil-water characteristic curve. Numerous experimental researches have been made on soil- water characteristic curve by many researchers such as **Fredlund and Xing, 1994**.

2. SOIL WATER CHARACTERISTIC CURVE

The soil-water characteristic curve for a soil is defined as the relationship between water content and suction for the soil. The water content defines the amount of water contained within the pores of the soil. In soil science, volumetric water content, θ, is most commonly used. In geotechnical engineering practice, gravimetric water content, *w*, which is the ratio of the mass of water to the mass of solids, is most commonly used. The degree of saturation, *S*, is another term commonly used to indicate the percentage of the voids that are filled with water. The above variables have also been used in a normalized form where the water contents are referenced to residual water content (or to zero water content) ,**Fredlund and Xing, 1994**.

There are two defining breaks along most soil water characteristic curve SWCC and these are referred to as the “air entry value” of the soil and the “residual value” of the soil. These points are illustrated in **Fig.1**, the air entry value is the point at which the difference between the air and water pressure becomes sufficiently large such that water can be displaced by air from the largest pore space in the soil. The residual degree of saturation is the point at which a further increase in suction fails to displace a significant amount of water, **Brooks and Corey, 1964.**

In this paper the soil-water characteristic curve relationship has been used to estimate the hydraulic conductivity.

3. COEFFICIENT OF PERMEABILITY FOR UNSATURATED SOIL

The coefficient of permeability *k* of an unsaturated soil is not a constant. The coefficient of permeability depends on the volumetric water content θ, which, in turn, depends upon the soil suction, ψ. When the coefficient of permeability at any soil suction, $k(\psi)$, is referenced to the saturated coefficient of permeability *ks*, the relative coefficient of permeability, $k_r(\psi)$, can be written as follows

k_s, the relative coefficient of permeability, $k_r(\psi)$, can be written as follows:

$$k_r(\psi) = \frac{k(\psi)}{k_s} \qquad (1)$$

The relative coefficient of permeability as a function of volumetric water content, $k_r(\theta)$, can be defined similarly. The relative coefficient of permeability, ($k_r(\psi)$ or $k_r(\theta)$), is a scalar function. The volumetric water content, θ, can be used in its normalized form, which is also referred to as the relative degree of saturation:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (2)$$

where:

Θ = the normalized volumetric water content or relative degree of saturation,

θ_s= the saturated volumetric water content, and

θ_r= the residual volumetric water content.

Degree of saturation, *S*, which indicates the percentage of the voids filled with water, is often used in place of the normalized water content, Θ, **Frendlund and Xing, 1994.**

4. MODELS FOR PREDICTION THE COEFFICIENT OF PERMEABILITY OF UNSATURATED SOIL

The coefficient of permeability for an unsaturated soil is primarily predicted from the soil-water characteristic curve. There are two approaches to obtain the permeability function of an unsaturated soil: (i) empirical equations, and (ii) statistical models. Several measured permeability data are required to use an empirical equation. A statistical model can be used to predict the permeability function when the saturated coefficient of permeability, k_S, and the soil-water characteristic curve are available. Several empirical equations for the permeability function of unsaturated soils are listed in **Table 1**. These equations can be used in engineering practice when measured data are available for the relationship between the coefficient of permeability and suction, $k(\psi)$, or for the relationship between the coefficient of permeability and the water content, $k(\theta)$, **Frendlund and Xing et al., 1994**.

Two hydraulic conductivity models built upon statistical pore size distributions that have received considerable attention in geotechnical engineering practice are the van **Genuchten, 1980 and Fredlund, et al., 1994** models**.** Both allow concurrent modeling of the soil-water characteristic curve and the hydraulic conductivity function.

Van Genuchten, 1980, proposed a flexible closed-form analytical equation for the relative hydraulic conductivity function $k_r(\psi)$ by substituting equation of Gardner (1958) into the statistical conductivity models proposed by **Burdine, 1953 and Mualem, 1976** as follows:

$$k_r(\psi) = \frac{\left\{1 - (a_{vg}\psi)^{n_{vg}-1}.\left[1 + (a_{vg}\psi)^{n_{vg}}\right]^{-m_{vg}}\right\}^2}{\left[1 + (a_{vg}\psi)^{n_{vg}}\right]^{m_{vg}/2}} \qquad (3)$$

where

ψ = soil suction (kPa);

a =model parameter related to air-entry value (suction value at which air starts to enter largest pores in the soil);

n = model parameter related to pore size distribution of the soil;

m = model parameter related to the asymmetry of the SWCC model curve.

Fredlund et al.و 1994, combined **Fredlund and Xing,1994**, equations with the statistical pore size distribution model of **Childs, and Collis-George 1950** to obtain a model for the relative hydraulic conductivity function as:

$$k_r(\psi) = \frac{\int_{\ln(\psi)}^{b} \frac{\theta(e^y) - \theta(\psi)}{e^y} \theta`(e^y)\, dy}{\int_{\ln(\psi_{av})}^{b} \frac{\theta(e^y) - \theta_s}{e^y} \theta`(e^y)\, dy} \quad (4)$$

Where:

y: is a dummy variable of integration representing ln(θ),
b = $\ln(10^6)$kPa,
ψ= soil suction (kPa);
ψ_{aev} : is the air-entry pressure,
θ': is the derivative with respect to ψ.

5. PREVIOUS WORKS ON UNSATURATED HYDRAULIC CONDUCTIVITY

Chiu and Shackelford 1998, studied the hydraulic conductivity of compacted sand-kaolin mixture. The measured unsaturated hydraulic conductivity ($k_{measured}$) values are compared with predicted unsaturated hydraulic conductivity ($k_{prediction}$) values using the Brooks-Corey-Burdine and van Genuchten-Mualem relative hydraulic conductivity functions. In general, the accuracy of ($k_{prediction}$) decreases with an increase in kaolin content or an increase in ψ_m. In addition, $k_{measured}$ tends to be under predicted for kaolin contents of 10 and 30% at relatively high suctions (1.0 m $<\psi_m<$6.0 m) and overpredicted for kaolin contents of 0 and 5% at relatively low suctions (0.1m $<\psi_m<$1.0 m). For a given kaolin content and ψ_m, $k_{\mathbf{prediction}}$ based on the Brooks-Corey-Burdine function tends to be more accurate than $k_{\mathbf{prediction}}$ based on the van Genuchten-Mualem function. Finally, for 1.0 m $<\psi_m<$6.0 m, $k_{\mathbf{prediction}}$ based on analysis using the maximum volumetric water content (θ_m) attained under steady-state flow conditions typically is more accurate than $k_{\mathbf{prediction}}$ based on analysis using the saturated volumetric water content, θ_s, where θ range between (84-90)% of θ_m.

Vanapalli et al., 2005, proposed a simple expression to estimate the unsaturated hydraulic conductivity of coarse-grained soils. A technique was proposed using a relationship between the relative conductivity k_r and the normalized degree of saturation, which is referred as the adjusted degree of saturation, Sγ. To estimate the unsaturated hydraulic conductivity the grain size distribution, the porosity, the degree of saturation (or water content), the saturated permeability of the soil, are required. The mathematical relationship is expressed as a normalized function:

$$K_r = s^{7.9\gamma} = \Theta^{7.9\gamma} \quad (5)$$

A relationship between the fitting parameter, γ and the index soil properties such as the porosity, and the fine content is proposed. The expression is:

$$\gamma = 0.012(1/n\ [clay\%]^2 + [silt\%]) + 0.38 \quad (6)$$

Gao et al. 2008, studied permeability of unsaturated remolded clay under different compaction conditions. Five specimens were compacted under different water contents with standard Proctor compaction effort to examine the influence of compacted water content on the permeability of unsaturated clay. The first specimen was compacted at optimum water content, which is 18.4%; the second and third samples were compacted wet of optimum water content, their compaction water content were 20.4% and 22.4%, respectively. The fourth and fifth specimens were compacted dry of optimum water content, 16.4% and 14.4% were their compaction water respectively. Three specimens were compacted using reduced, standard, and modified Proctor compaction efforts in order to analyze effects of compaction effort on permeability of remolded clayey soil. The results indicated that the permeability coefficient decreases with the increase of compaction water content, and the difference reduces with the increase of suction, and permeability coefficient can be assumed identical when the suction reach to 1000 kPa. The permeability coefficient of samples compacted with standard Proctor compaction effort and reduced Proctor compaction effort are very similar. The value of k_w (modified) k_w (standard) is about 1/100 in saturated state, and which increases as the suction increases.

When the suction reaches 1000kPa, the value decreases to 1/10 gradually.

Lamara et al.,2008, studied the reliability of indirect methods for predicting the hydraulic conductivity of dune sand widely present in the Algerian Sahara. The results obtained were promising and test clearly of the major contribution that may bring along the hydraulic property prediction models to the unsaturated soil mechanics practice. **Zapata's et al. model,2000,** was used to evaluate the soil water characteristic curve depending on the grain size distribution information. The unsaturated hydraulic conductivity has been predicted, using two statically based models **Mualem-van Genuchten,1980 and Fredlund et al.,1994,** beside **Vanapalli et al.,2005,** empirical model. The results obtained were promising and attested clearly that some models can yield good predictions.

6. EXPERIMENTAL WORK

In this paper, the aim of experimental work is to define the soil water characteristic curve (SWCC) by measurement of the soil suction.

A soil sample was collected from a site east of Baghdad. The physical properties of this soil was studied by conducting a series of tests in the laboratory, these include: specific gravity, Atterberg limits, grain size distribution by sieve analysis and hydrometer, compaction test and permeability test (falling head). The total and matric suction are measured by the filter paper method at different degrees of saturation.

A brown clayey soil was brought from a site east of Baghdad. Standard tests are performed to determine the physical properties of the soil. Details are given in **Table 2**. Grain size distribution of the soil used revealed 6 % sand, 24% silt and 70% clay as shown in **Fig. 2**. According to the Unified Soil Classification System USCS the soil is classified as CL.

7. TOTAL AND MATRIC SUCTION OF SOIL MEASUREMENT BY FILTER PAPER METHOD

The filter paper method has long been used in soil science and engineering practice and it has recently been accepted as an adaptable test method for soil suction measurements because of its advantages over other suction measurement devices. Basically, the filter paper comes to equilibrium with the soil either through vapor (total suction measurement) or liquid (matric suction measurement) flow. At equilibrium, the suction value of the filter paper and the soil will be equal. After equilibrium is established between the filter paper and the soil, the water content of the filter paper disc is measured. Then, by using filter paper water content versus suction calibration curve, the corresponding suction value is found from the curve. This is the basic approach suggested by ASTM Standard Test Method for Measurement of Soil Potential (Suction) Using Filter Paper **ASTM D 5298**. In other words, **ASTM D 5298** employs a single calibration curve that has been used to infer both total and matric suction measurements. The **ASTM D 5298** calibration curve is a combination of both wetting and drying curves, as shown in **Fig.3**.

8. MEASUREMENT OF SOIL SUCTION

Glass jars that are between 250 to 500 ml volume sizes are readily available and can be easily adopted for suction measurements. Glass jars, especially, with 3.5 to 4 inch (88.9 to 101.6 mm) diameter can contain the 3 inch (76.2 mm) diameter Shelby tube samples very nicely. A testing procedure for total suction measurements using filter papers can be outlined as will be described in the following sections **,Bulut et al., 2001.**

9. EXPERIMENTAL PROCEDURE

1. Use a container that a Shelby-tube soil sample can be fit into easily without the disturbance of the soil sample.
2. Cut the soil sample into two halves for matric suction measurements.
3. Make sure that the surfaces of the soil samples are smooth and flat for establishing an intimate contact between the soil sample and the filter paper for matric suction measurements.
4. For matric suction measurements, insert a single Whatman No. 42 filter paper in between two larger in diameter protective filter papers. Put the other half of the soil sample on top, keeping the sandwiched filter papers in between and in intimate contact with the soil samples. Tape the two pieces of the soil sample together.
5. Insert a clean PVC O-ring, with the sharp edge facing up, on top of the soil sample for total suction measurements. Place two of Whatman No. 42 filter paper on top of the ring.
6. Put the lid on and tape it tight to prevent any moisture exchange between the air inside and air outside of the jar, insert the glass jar into a well-insulated container for suction equilibrium.
7. Soil suction measurement set up, as described in the previous steps, will be kept in a temperature-controlled environment for at least one week.
8. Previous steps are repeated for every soil sample.
9. After at least one week of equilibrium period, record all the weights with their corresponding tin numbers.
10. Remove a glass jar from the temperature controlled container. Time is critical at this stage and thus it is suggested that two people share the work, the time that the filter papers are exposed to the lab environment should be minimal, preferably less than a few seconds.
11. Open the glass jar and quickly carry the filter paper to the moisture tin using tweezers, in less than a few seconds, immediately close the lid of the moisture tin with the wet filter paper inside.
12. After closing the lid of the moisture tin, immediately weigh the tin with the wet filter paper inside. This is a total suction measurement.
13. Continue with the matric suction measurement by removing the tape that was holding the soil samples together. Remove the filter paper that was sandwiched between the two protective filter papers. Immediately carry the filter paper to the moisture tin, close the lid of the moisture tin and weigh the tin with the wet filter paper inside. This is a matric suction measurement.
14. After opening all the glass jars and recording the weight of the moisture tins with the wet filter papers inside, carry them to a hot oven with the lids half open. Leave them in the oven for at least 10 hours. Before taking them out from the oven, close their lids for equilibrium and leave them in the oven for about 5 minutes.
15. Weigh the hot tin with the dry filter paper inside.
16. Calculate the moisture content of each filter paper for both total and matric suction measurements.
17. Obtain the suction value from an appropriate calibration curves or by these relations. These steps are documented in **plates 1 to 6.**

10. INPUT DATA IN SOIL VISION

Total and matric suction of the soil samples are measured by remolding the samples at different degrees of saturation (40%, 50%, 60%, 70%, 80%, and 90%) using the filter paper method. A sample of the data documented during the measurement of soil suction is shown in **Table 3**. **Figs.4 and 5** show the relationship between the total and matric suction and the degree of saturation, respectively.

From Fig.4, it can be shown that the s[illegible] 0.001 0.01 0.1 [illegible]il decreases with increase of degree of saturation and the rate of decreasing in matric suction is not equal to the rate of increase of the degree of saturation.

From the program (Soil Vision), and after inputting all the required properties of the soils used in this analysis, (i.e., total unit weight, dry unit weight, liquid limit, plasticity index, void ratio, porosity, matric suction value, degree of saturation, and grain size distribution), the soil water characteristic curve is predicted (relation between the gravitation water content and the matric suction) through applying fitting methods, such as the method proposed by **Fredlund and Xing,1994 and van Genuchten, 1980,** for fitting the soil water characteristic curve **Fig.6**.

11. ESTIMATED UNSATURATED HYDRAULIC CONDUCTIVITY (K)

In this paper, Soil Vision program has been used in order to find the properties of soil such as volumetric water content and unsaturated hydraulic conductivity. After determination of the relation between the volumetric water content and matric suction using fitting of the Fredlund and Xing model at every degree of saturation, a relationship between the hydraulic conductivity and matric suction can be estimated from Soil Vision program.

The Fredlund and Xing model (1994) in Soil Vision program is used to calculate unsaturated hydraulic conductivity as the following equation:

$$k = k_{sat}\frac{\int_{\psi}^{\psi_r}\frac{\theta(y)-\theta(\psi)}{y^2}\theta`y dy}{\int_{\psi}^{\psi_r}\frac{\theta(y)-\theta_s}{y^2}\theta`y dy} \qquad (7)$$

y: is a dummy variable of integration representing ln(ψ),

ψ = soil suction (kPa),

ψ_r is the suction corresponding to the residual water content θ_r,

θs = the saturated volumetric water content,

θ`: is the derivative with respect to ψ.

The most variable parameter in the Soil Vision program is saturated hydraulic conductivity and Fredlund and Xing fit of soil-water characteristic carve by fitting in each degree of saturation from 100% to 40%. Finally, the unsaturated hydraulic conductivity carve is predicted in **Fig.7** for different degrees of saturated.

A steep permeability function indicates a rapid reduction in the water coefficient of permeability for a small increase in matric suction. In this case, the quantity of water flow in to the unsaturated zone is considerably reduced.

12. CONCLUSIONS

- From the soil water characteristic curve (SWCC) which was determined by experimental method (i.e. filter paper method) for the study soil, the matric suction values were found to increase by about (15-63)% with decrease of the degree of saturation from 90% to 40%, and the rate of increase is not equal to rate of decrease in degree of saturation.
- From the soil water characteristic curve (SWCC), the unsaturated hydraulic conductivity value was calculated, and was found to decrease by about (38-99) % with increase of the matric suction for each degree of saturation.

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Table 1. Empirical equations for the unsaturated coefficient of permeability *k*(θ)),**Frendlund et al.,1994.**

Function	Reference
$k_r = \psi^n$, where $\Theta = {(\theta - \theta_r)}/{(\theta_s - \theta_r)}$	Averjanov (1950)
$k = k_s\left(\frac{\theta}{\theta_s}\right)^n$	Campbell (1973)
$k = k_s \exp[\alpha(\theta - \theta_s)]$	Davidson et al. (1969)
$k = k_s$, for $\psi \le \psi_{aev}$ $k_r = \left({\psi}/{\psi_{aev}}\right)^{-n}$ for $\psi \ge \psi_{aev}$	Brooks and Corey(1964)
$k_r = \exp(-\alpha\psi)$ $k = k_s/(\alpha\psi^n + 1)$	Gardner (1958)
$k = a\psi + b$	Richards (1931)
$k = k_s$ for $\psi \ge \psi_{aev}$ $k_r = \exp[-\alpha(\psi - \psi_{ave})]$ for $\psi_{aev} \le \psi \le \psi_1$ $k = k_1\left(\frac{\psi}{\psi_1}\right)$ for $\psi > \psi_1$	Rijtema (1965)
$k = \alpha\psi^{-n}$	Wind (1955)

Table 2. Index properties of the soils**.**

Index property	Index value
Liquid limit % (LL)	49.8
Plasticity index % (PI)	25
Specific gravity (Gs)	2.79
Sand %	6
Silt %	24
Clay%	70
Classification (USCS)	CL
Optimum moisture content	20.32%
Dry unit weight (kN/m^3)	17.13

Table 3. Measurement of soil suction using filter paper method.

MEASUREMENT OF SOIL TOTAL SUCTION USING FILTER PAPER							
Degree of Saturation %		**40**	**50**	**60**	**70**	**80**	**90**
Water Content of Filter Paper %	**Wf**	**10.3**	**11.6**	**14.7**	**15.3**	**16.5**	**18**
Total Suction, log kPa	**h_t**	**4.5246**	**4.4233**	**4.1819**	**4.1351**	**4.0413**	**3.9248**
MEASUREMENT OF SOIL MATRIC SUCTION USING FILTER PAPER							
Degree of Saturation %		**40**	**50**	**60**	**70**	**80**	**90**
Water Content of Filter Paper	**Wf**	**25.3**	**32**	**46**	**55.3**	**71.4**	**86**
Matric Suction, log kPa	**h_t**	**3.3561**	**2.8342**	**2.3985**	**1.7935**	**1.4481**	**1.251**

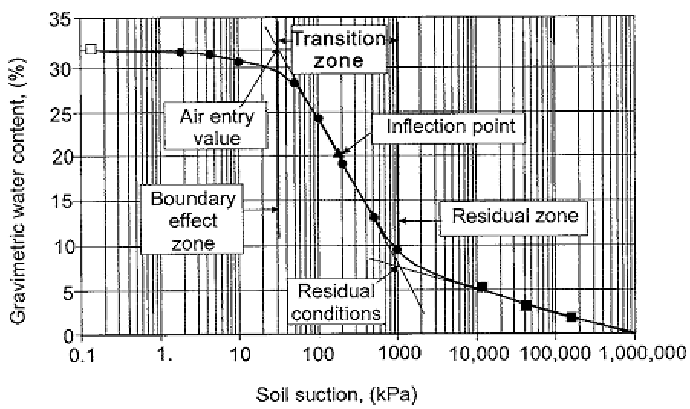
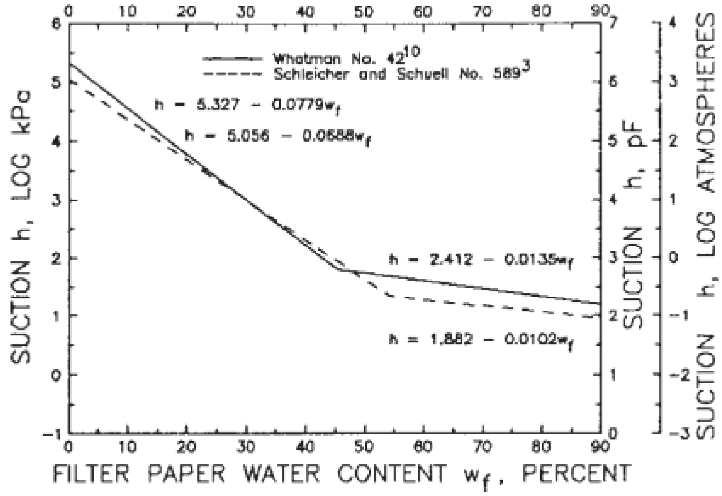


Figure 1. Illustration of the in situ zones of desaturation defined by a soil – water characteristic curve, **after Fredlund, 2006.**



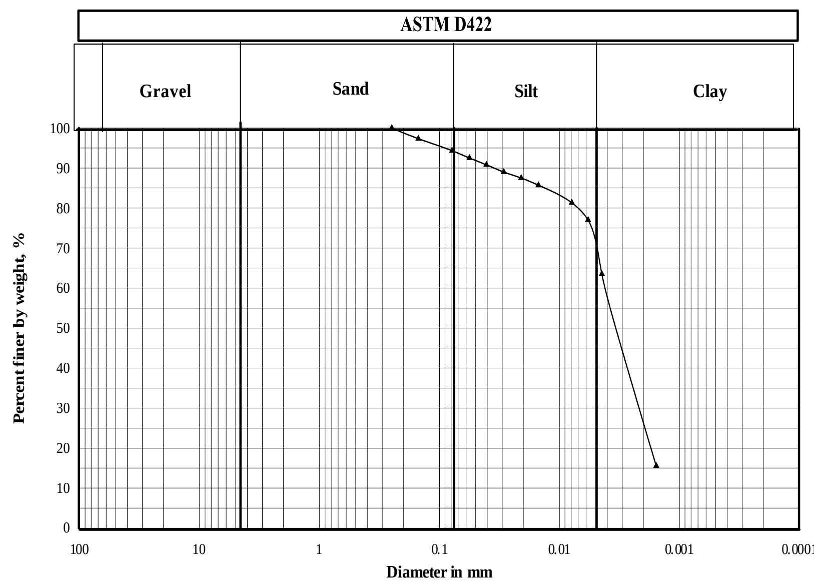
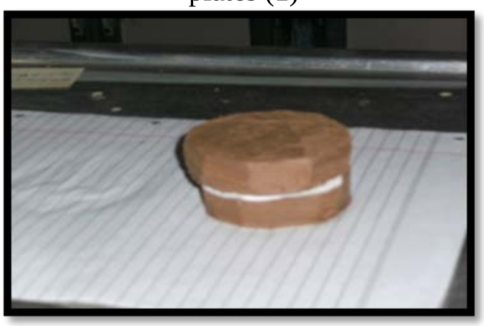


Figure 2. Grain size distribution of the soil. used.

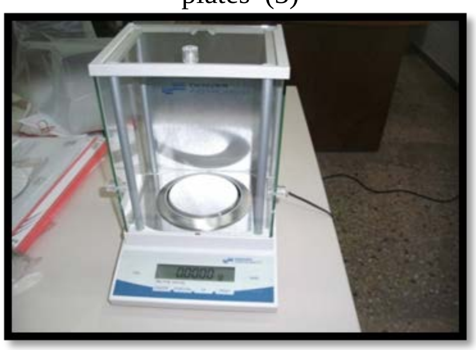
plates (1)

plates (2)



plates (3)

plates (4)



plates (5)

plates (6)

Figure 3. Calibration suction-water content curves for wetting of filter paper (from **ASTM-5298-03).**

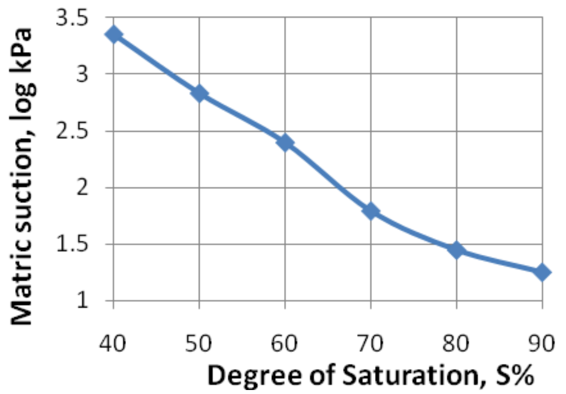


Figure 4. Relationship between the matric suction and degree of saturation.

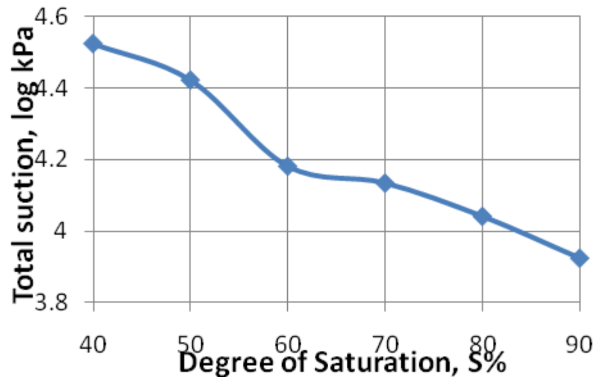


Figure 5. Relationship between the total suction and degree of saturation.

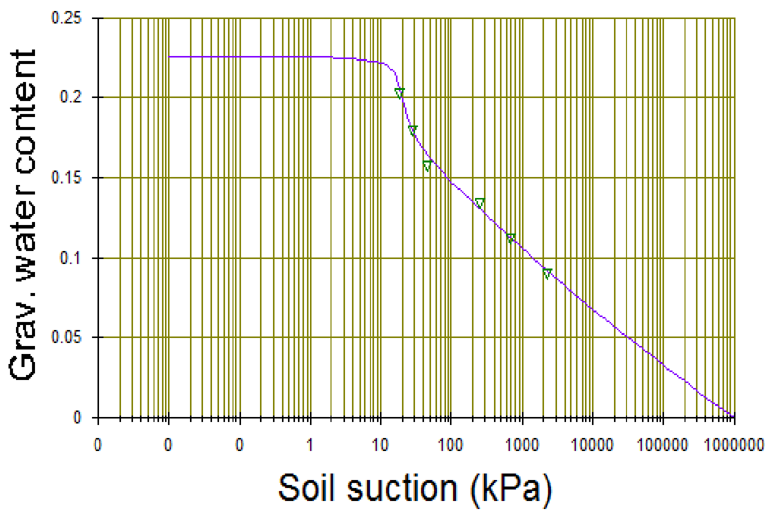
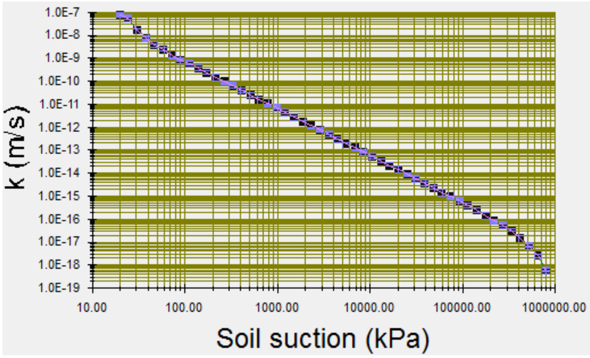
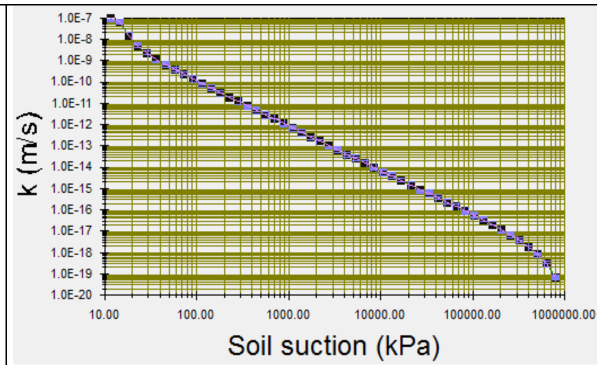


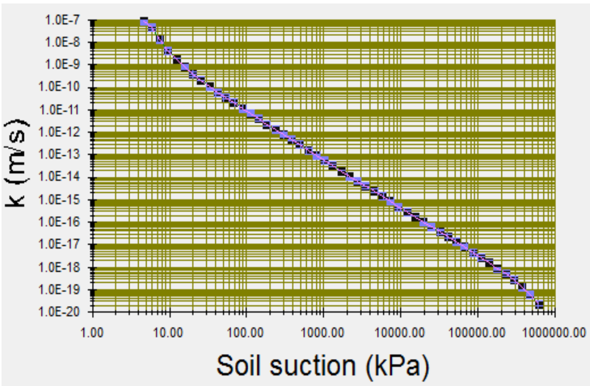
Figure 6. Relationships between the gravitational water content and the matric suction obtained by the program Soil Vision by using Fredlund and Xing (1994) fitting.



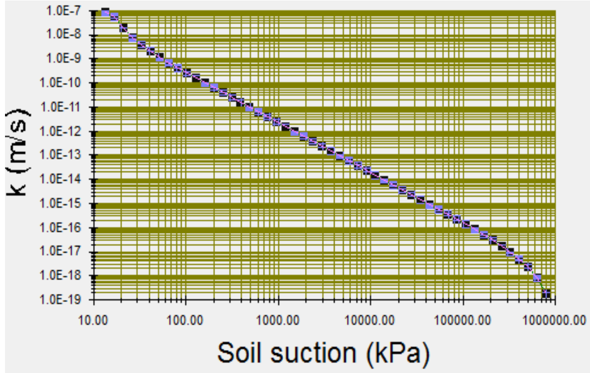
a-Hydraulic conductivity at S = 100%.



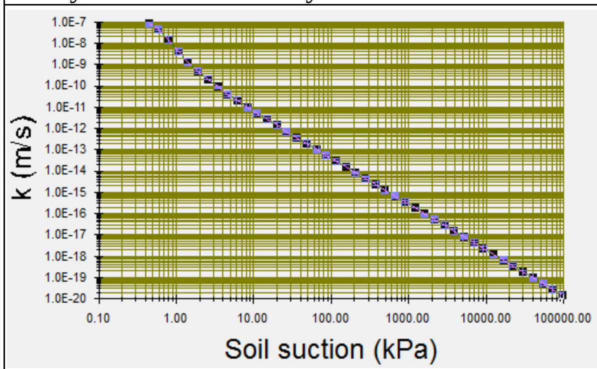
b-Hydraulic conductivity at S = 90%.



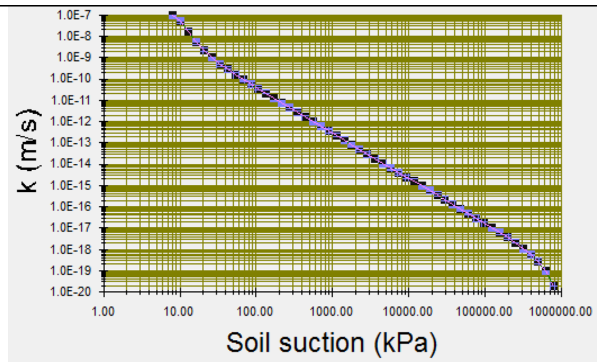
c- Hydraulic conductivity at S =80% .



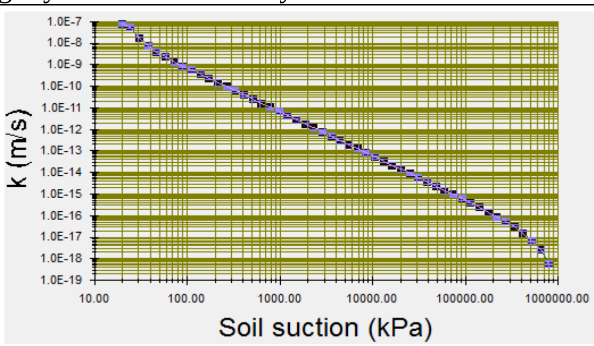
d- Hydraulic conductivity at S =70%.



g-Hydraulic conductivity at S = 60%.



h-Hydraulic conductivity at S =50%



j- Hydraulic conductivity at S =40% .

Figure 7. Relationships between the hydraulic conductivity and the matric suction for different degrees of saturation obtained by the program soil vision.