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Determination of the Shear Strength, Permeability and Soil Water Characteristic Curve of Unsaturated Soils from Iraq

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Abstract

The soil water characteristic curve (SWCC) defines the relationship between the amount of water in the soil and soil suction. The SWCC has been used as a tool either directly or indirectly in the prediction of the shear strength parameter and coefficient of permeability. In this paper, three undisturbed soil samples were collected from three sites within Baghdad city, Al-Rasafa region. The physical properties of these soils were studied by conducting a series of tests in the laboratory. For each sample, the SWCC is measured by the filter paper method. Fitting methods are applied through the program (Soil Vision), after indentifying the basic properties of the soil such as Attereberg limits, particle size distribution, specific gravity, void ratio, porosity and wet and dry unit weights. Then, the soil water characteristic curve is converted to relation correlating the void ratio and matric suction. The slope of the latter relation can be used to define the H–modulus function which is used for finite element analysis of unsaturated soil. Estimation the coefficient of permeability of unsaturated soil was also made and the undrained shear strength was measured for each value of matric suction. It was concluded that the matric suction value increases with decrease of the degree of saturation, and the undrained shear strength increases with increase of matric suction. Also, the coefficient of permeability decreases with increase of matric suction.

Mathematics Subject Classification : Unsaturated soil.
Keywords: Total suction, matric suction, filter paper, soil water characteristic curve.

1 Introduction

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There are many practical situations involving unsaturated soils that require an understanding of the seepage, volume change, and shear strength characteristics. In fact, there is often an interaction among, and a simulation interest in all three of the aspects of unsaturated soil mechanics. Typically, a flux boundary condition produces an unsteady-state saturated/unsaturated flow situation which results in volume change and a change in the shear strength of the soil. The change in shear strength is generally translated into a change in factor of safety.

The stress state of an unsaturated soil can be described by any two of the three possible combinations of stress variables, namely: total normal stress (σ), pore air pressure (ua), and pore water pressure (uw). For an unsaturated soil, two stress state variables are used to describe its shear strength, while only one stress state variable [i.e., effective normal stress, (σ – uw)] is required for a saturated soil. In the case of an unsaturated soil, the Mohr circles corresponding to failure conditions can be plotted in a three-dimensional manner. The three-dimensional plot has the shear stress as the ordinate and the two stress state variables, (σ - uw) and (ua – uw), as abscissas. The frontal plane represents a saturated soil where the matric suction is zero. On the frontal plane, the (σ – ua) axis reverts to the (σ – uw) axis since the pore-air pressure becomes equal to the pore-water pressure at saturation. The surface tangent to the Mohr circles at failure is referred to as the extended Mohr-Coulomb failure envelope for unsaturated soils. The cohesion intercept, c', and the slope angles, ø' and øb, are the strength parameters used to relate the shear strength to the stress state variables. The value of øb is consistently equal to or less than ø' [1].

The classical one – dimensional theory of consolidation is of central importance in saturated soil mechanics. The theory of consolidation predicts the change in pore-water pressure with respect to depth and time in response to change in total stress. The changes in pore-water pressure are used to predict the volume change. The application of total stress to unsaturated soil produces large instantaneous volume changes, but smaller volume changes with respect to time. The induced pore-water pressure is considerably smaller than the applied total stress. The more common boundary condition for unsaturated soil is a change in flux as opposed to a change in total stress for a saturated soil. Nevertheless, the theory of consolidation for unsaturated soils plays an important phenomenological role. It assists the engineer in visualizing complex mechanisms, providing a qualitative “feel” for the behavior of an unsaturated soil [1].

2 Soil Suction Concept

In general, porous materials have a fundamental ability to attract and retain water. The existence of this fundamental property in soils is described in engineering terms as suction or negative stress in the pore water. In engineering practice, soil suction is composed of two components: matric and osmotic suction [1]. The sum of matric and osmotic suction is called total suction. Matric suction comes from the capillarity, texture, and surface adsorptive forces of the soil. Osmotic suction arises from the dissolved salts contained in the soil water.

Soil suction can be determined using various techniques; an overview of the various methods can be found in: Fredlund and Rahardjo [1], Lee and Wray [2], Bulut and Leong [3], Pan et al., [4], Murray and Sivakumar [5], and others. A wide range of systems and methods to measure suction are available in the market. The filter paper method relies on the principle that when a filter paper is in contact with soil, it will absorb the moisture until the suction in the soil is equal to that in the filter paper. The method requires a calibration for suction versus water content relationship of the filter paper. The method can be used to measure either the total suction or matric suction depending on whether the filter paper and the soil are in contact. The main advantage of this method is its low cost as compared to other methods, and its applicability over a wide range of suction (full range of suction in case of contact filter paper). The filter paper method was evolved in Europe in the 1920 and came to the United States in 1937 with Gardner [6]. Since then, the filter paper method has been used and investigated by numerous researchers [7], [8], [9], [10], [11], who have tackled different aspects of the filter paper method.

3 Soil Water Characteristic Curve

The soil water characteristic curve (SWCC) defines the relationship between the amount of water in the soil and soil suction. The amount of water can be a gravimetric water content, w, volumetric water content, θ, or degree of saturation, S. The SWCC is also called the water retention curve, (WTC) or the capillary pressure curve. The SWCC divides soil behavior into three distinct stages of desaturation as shown in Fig. 1. The stages of desaturation are referred to as the "boundary effect stage" at low soil suction, the "transition stage" at intermediate soil suction, and the "residual stage" at the high soil suction that extend to 1,000,000 kPa [12].

There are two defining breaks along most 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 [13].

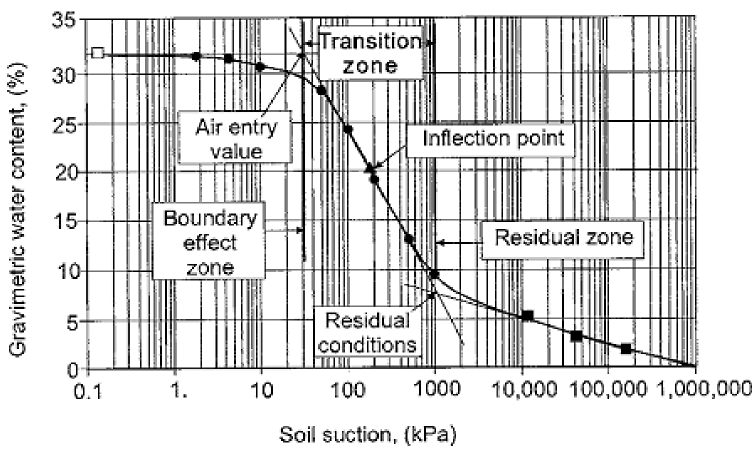


Figure 1**:** Illustration of the in situ zones of desaturation defined by a soil – water characteristic curve (after Fredlund) [12].

The general shape of the SWCC for various soils reflects the dominating influence of material properties including pore size distribution, gain size distribution, density, organic material content, clay content, and mineralogy on the pore water retention behavior [14].

In this paper, three undisturbed soil samples were collected from three sites within Baghdad city, Al-Rasafa region. For each sample, the SWCC is measured by the filter paper method. Then, the soil water characteristic curve is converted to relation correlating the void ratio and matric suction. The aim of this study is studying the effect of soil suction on some parameters of the soil, and then defining the H-modulus function which is necessary for analyzing unsaturated soil problems by the finite element method.

4 Experimental Program

In this study, the aim of experimental work is to define the soil water characteristic curve (SWCC) by measurement of the soil suction, the total and matric suction by the filter paper method at different degrees of saturation. A three undisturbed soil samples were collected from two sites within Baghdad city Al-Rasafa region; namely, soil 1 from depth (3.5 m), in this study referred to as (Rasafa 1), soil 2 from depth (9.5 m, and 3.5 m) referred to as (Rasafa 2, and Rasafa 3), respectively. The samples were subjected to testing program which included the following tests:

The specific gravity for the soils studied was determined according to ASTM D-854-00 [15]. The results are summarized in Table 1.

The liquid and plastic limit tests were carried out on the soil passing sieve No. 40 according to ASTM D-4318-00 [16]. The results are shown in Table 1.

For grain size distribution, wet sieving (by water), and hydrometer tests were carried out in accordance with ASTM-D-422-00 [17]. The grain size distribution of the three samples is shown in Fig. 2. The figure shows that all these soils are classified as silty clay according to "ASTM" classification, designated as (CL) for Rasafa 1 and Rasafa 2, and (CH) for Rasafa 3 according to the Unified Soil Classification System, and the percentage of clay is summarized in Table 1.

Table 1**:** Index properties of the soils

Site	Liquid Limit, LL (%)	Plastic Limit. PL (%)	Plasticity Index, PI (%)	Specific Gravity, Gs	% Clay
Rasafa 1	34	19	15	2.74	68.3
Rasafa 2	45	27	18	2.76	66.5
Rasafa 3	54	27	27	2.78	80.3

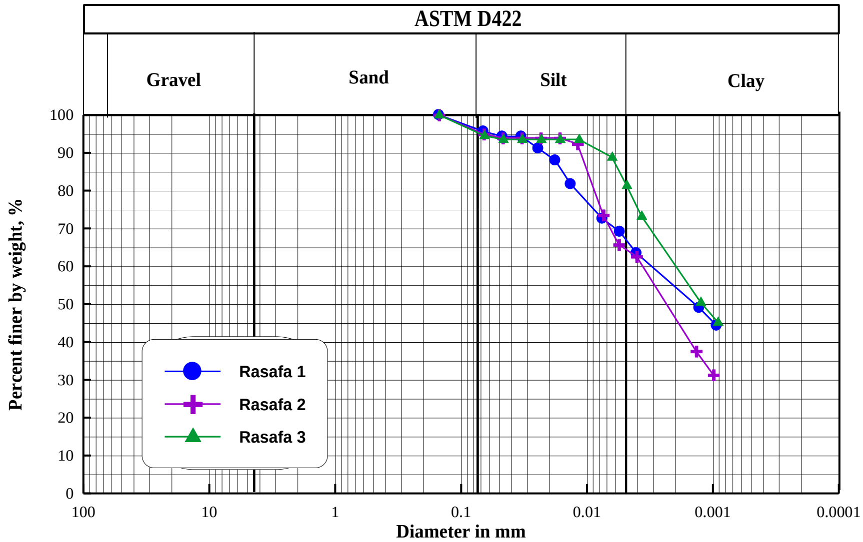


Figure 2**:** Grain size distribution.

4.1 Unconfined Compression Test

At first, unconfined compression test was carried out on undisturbed samples in accordance with ASTM-D-2166-00 [18]. Unconfined compression strength (qu), undrained shear strength of cohesive soil (Cu), and the relationship between the soil consistency and its unconfined compressive strength are shown in Table 2 and Figure 3.
Then the undrained shear strength (Cu) of each soil was measured by carrying out unconfined compression test through remolding the samples at different degrees of saturation (100%, 90%, 80%, and 70%), the results are summarized later in Figs. 7 to 9, and Table 5.

Table 2**:** Results of unconfined compression test for undisturbed samples

Site	qu (kPa)	Cu (kPa)	Consistency
Rasafa 1	269	134.5	Very stiff
Rasafa 2	215	107.5	Very stiff
Rasafa 3	132	66	Stiff

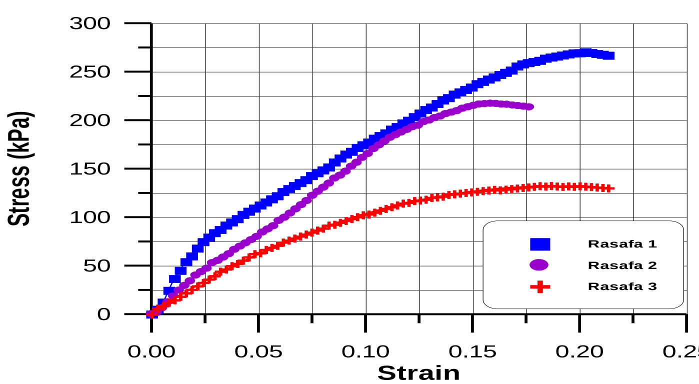


Figure 3**:** Stress – strain relationship from unconfined compression test for undisturbed samples.

4.2 Consolidation Test

One-dimensional consolidation test was carried out using the standard oedometer to determine the soil compressibility characteristics in accordance with ASTM- D2435-00 [19]. The pressure – void ratio relationships for the samples are drawn in Figure 4.
Also, the coefficient of permeability (k) was calculated from consolidation test according to the equation:

$$k = c_v m_v \gamma_w \tag{1}$$

Where: cv = coefficient of consolidation,
mv = coefficient of volume change, and
γw = water unit weight.
The results of the three soils are summarized in Table 3.

Table 3: Coefficient of permeability for the three types of soil

Type of soil	k (m/sec)
Rasafa 1	2.55 x 10-10
Rasafa 2	2.78 x 10-10
Rasafa 3	2.85 x 10-10

In Table 4 which is based in the description of soil permeability on the Unified Soil Classification, as cited by Bowles [20], emphasized the accuracy of the permeability values obtained in this work.

Table 4: Order-of-magnitude values for permeability based on description of soil and by Unified Soil Classification, m/s [20]

1	**2**	**3**	**4**
10^{0} – 10^{-2}	10^{-2} – 10^{-5}	10^{-5} – 10^{-9}	10^{-9} – 10^{-11}
Clean gravel GW, GP	Clean gravel and sand mixtures GW,GP,SW, SP, GM	Sand-silt mixture SM, SL, SC	Clays

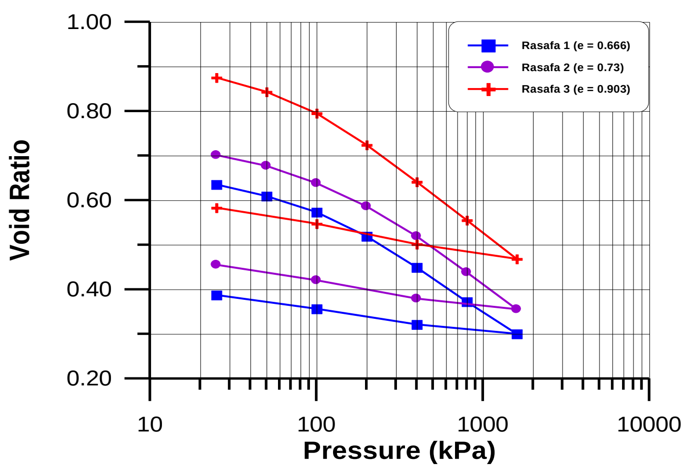


Figure 4: Results of oedometer test.

4.3 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 [21]. In other words, ASTM D 5298-03 employs a single calibration curve that has been used to infer both total and matric suction measurements. The ASTM D 5298-03 calibration curve is a combination of both wetting and drying curves, as shown in Figure 5.

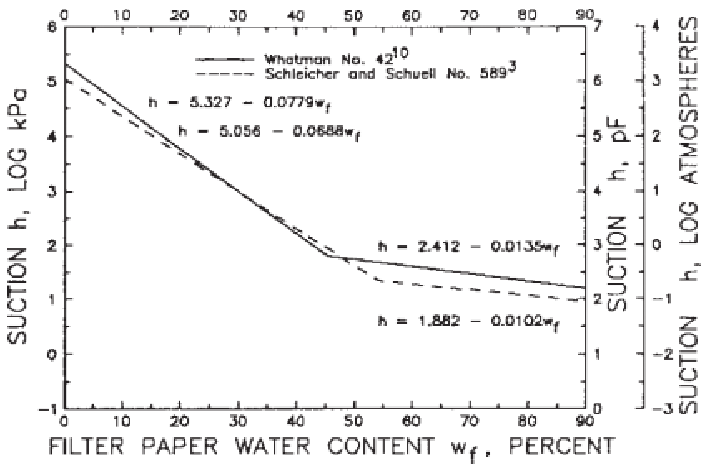


Figure 5**:** Calibration suction-water content curves for wetting of filter paper [25].

1) Measurements of total suction of soil:

A testing procedure for total suction measurements using filter papers can be outlined as follows [22]:

1. At least 75 percent by volume of a glass 500 ml. volume jar is filled up with the soil; the smaller the empty space remaining in the glass jar, the smaller the time period that the filter paper and the soil system requires to come to equilibrium.
2. A ring type support, which has a diameter smaller than filter paper diameter and about 1 to 2 cm in height, is put on top of the soil to provide a non-contact system between the filter paper and the soil. Care must be taken when selecting the support material; materials that can corrode should be avoided, plastic or glass type materials are much better for this job.
3. Two filter papers; one on top of the other are inserted on the ring using tweezers. The filter papers should not touch the soil, the inside wall of the jar, and underneath the lid in any way.
4. Then, the glass jar lid is sealed very tightly with plastic tape.

5. Steps 1, 2, 3, and 4 are repeated for every soil sample.
6. After that, the glass jars are put into the ice-chests in a controlled temperature room for equilibrium.

Researchers suggest a minimum equilibrating period of one week [21], [10]. After the equilibration time, the procedure for the filter paper water content measurements can be as follows [22]:

1. Before removing the glass jar containers from the temperature room, all aluminum cans that are used for moisture content measurements are weighed to the nearest 0.0001 g. accuracy and recorded.
2. After that, all measurements are carried out by two persons. For example, while one person is opening the sealed glass jar, the other is putting the filter paper into the aluminum can very quickly (i.e., in a few seconds) using tweezers.
3. Then, the weights of each can with wet filter paper inside are taken very quickly.
4. Steps 2 and 3 are followed for every glass jar. Then, all cans are put into the oven with the lids half-open to allow evaporation. All filter papers are kept at 105 ±5oC temperature inside the oven for at least 10 hours.
5. Before taking measurements on the dried filter papers, the cans are closed with their lids and allowed to equilibrate for about 5 minutes. Then, a can is removed from the oven and put on an aluminum block (i.e., heat sinker) for about 20 seconds to cool down; the aluminum block functions as a heat sink and expedites the cooling of the can. After that, the can with the dry filter paper inside is weighed very quickly. The dry filter paper is taken from the can and the cooled can is weighed again in a few seconds.
6. Step 5 is repeated for every can.

2) Measurements of matric suction of soil

Soil matric suction measurements are similar to the total suction measurements except instead of inserting filter papers in a non-contact manner with the soil for total suction testing, a good intimate contact should be provided between the filter paper and the soil for matric suction measurements. Both matric and total suction measurements can be performed on the same soil sample in a glass jar as shown in Figure 6. A testing procedure for matric suction measurements using filter papers can be outlined as follows [22]:

1. A filter paper is sandwiched between two larger size protective filter papers. The filter papers used in suction measurements are 5.5 cm in diameter, so either a filter paper is cut to a smaller diameter and sandwiched between two 5.5 cm papers or bigger diameter (bigger than 5.5 cm) filter papers are used as protective.
2. Then, these sandwiched filter papers are inserted into the soil sample in a very good contact manner (i.e., as in Figure 6). An intimate contact between the filter paper and the soil is very important.
3. After that, the soil sample with embedded filter papers is put into the glass jar container. The glass container is sealed up very tightly with plastic tape.
4. Steps 1, 2, and 3 are repeated for every soil sample.
5. The prepared containers are put into ice-chests in a controlled temperature room for equilibrium. Researchers suggest an equilibration period of (3 to 5) days for matric suction testing [25], [14]. However, if both matric and total suction measurements are performed on the same sample in the glass jar, then the final equilibrating time will be at least 7 days of total suction equilibrating period. The procedure for the filter paper

water content measurements at the end of the equilibration is exactly same as the one outlined for the total suction water content measurements. After obtaining all the filter paper water contents, the appropriate calibration curve may be employed to get the matric suction values of the soil samples.

6.

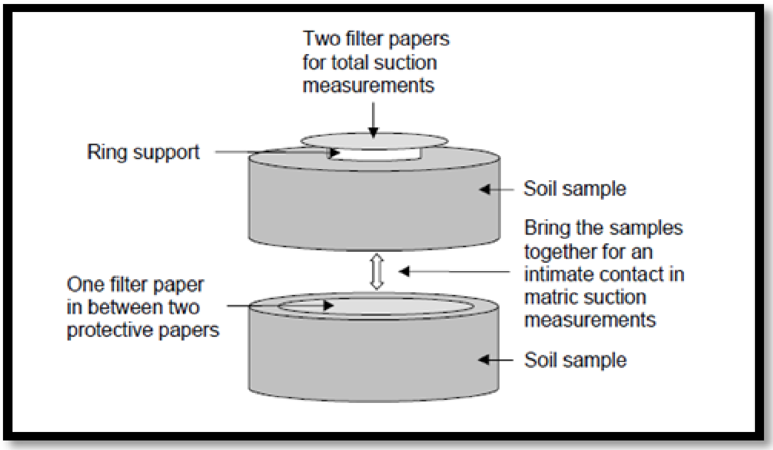


Figure 6**:** Total and matric suction measurement [22].

5 Results and Discussion

5.1 Undrained Shear Strength

The undrained shear strength (Cu) of each soil was measured by carrying out unconfined compression test through remolding the samples at different degrees of saturation (100%, 90%, 80%, and 70%). The results demonstrate that the unconfined compressive strength (qu) increases with the decrease of saturation (S), and consequently increase of undrained shear strength (Cu), while the angle of internal friction (ø) remained constant (i.e. equal to zero). This finding is compatible with Fredlund and Rahradjo [1] and Oh and Vanapalli [23]. The results of unconfined compression test are shown in Table 5 and Figs**.** 7 to 9 for the three sites.

Table 5**:** Results of unconfined compression test on remolded samples

Cu (kPa)	qu (kPa)	S (%)	Type of Soil
135	270	100%	Rasafa 1
143.5	287	90%	
155.5	311	80%	
164.5	329	70%	
102.5	205	100%	Rasafa 2
113.5	227	90%	
119	238	80%	
126	252	70%	
65	130	100%	Rasafa 3
75.5	151	90%	
82	164	80%	
88	*176*	*70%*	

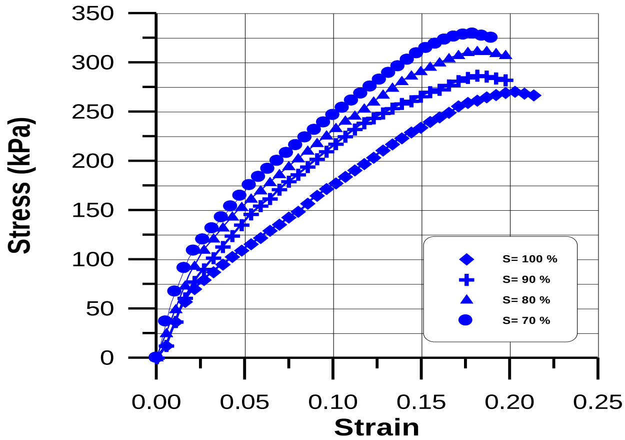


Figure **7:** Results of unconfined compression test on remolded samples from (Rasafa 1) site at different degrees of saturation.

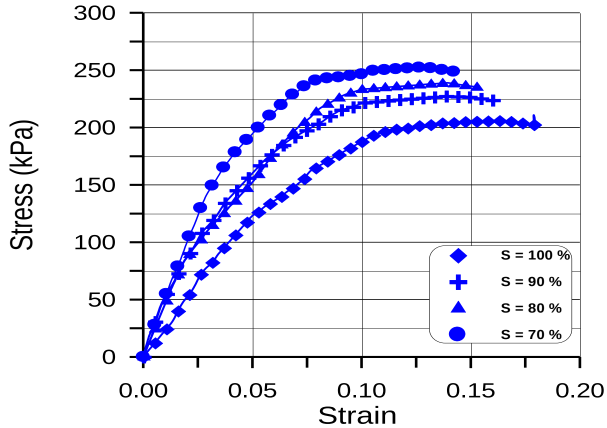


Figure 8**:** Results of unconfined compression test on remolded samples from (Rasafa 2) site at different degrees of saturation.

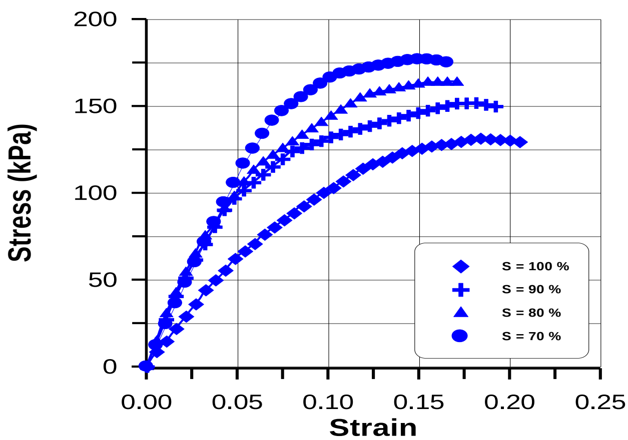


Figure 9**:** Results of unconfined compression test on remolded samples from (Rasafa 3) site at different degrees of saturation.

5.2 Suction versus Degree of Saturation

Total and matric suction of each soil sample were measured by remolding the samples at different degrees of saturation (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 6.

Figs. 10 and 11 show the relationship between the total and matric suction and the degree of saturation, respectively. From these figures, it can be shown that the suction of the soil 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. It is also noticed that the suction values for Rasafa 1 soil are higher than the suction values for Rasafa 2 & 3 soils at the same degree of saturation. This is due to the ability of the soil from Rasafa 1 to retention of water is more than the soil from Rasafa 2 & 3 because the void ratio for Rasafa 1 is smaller than that for Rasafa 2 & 3.

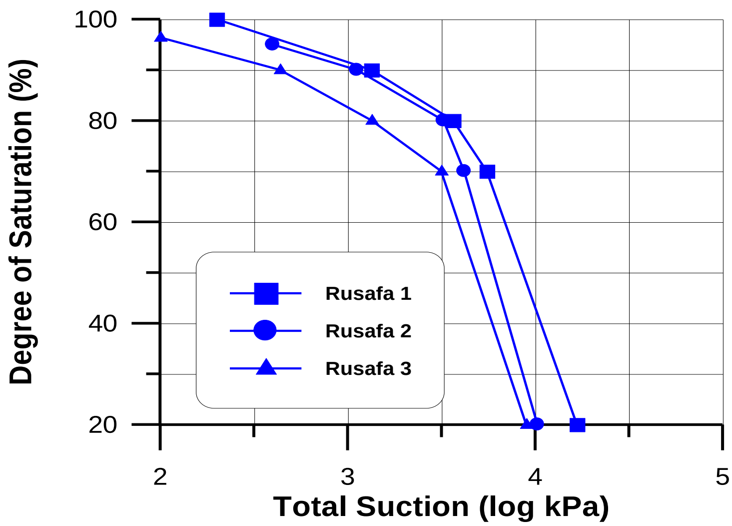


Figure 10**:** Relationship between the total suction and degree of saturation.

Table 6**:** Measurement of soil suction using filter paper – data sheet

MEASUREMENT OF SOIL TOTAL SUCTION USING FILTER PAPER					
SAMPLE NAME: RASAFA 1					
DATE TESTED: 23-1-2011			DATE SAMPLE: 16-1-2011		
100	90	80	70	Degree of Saturation %	
4	3	2	1	Moisture Tin No.	
Top	Top	Top	Top	Top Filter Paper (circle)(twofilters)	
0.5822	0.5651	0.5651	0.5482	M1	Mass of Wet Filter Paper, g
0.4193	0.4405	0.4607	0.4555	M2	Mass of Dry Filter Paper, g
0.1629	0.1596	0.1044	0.0927	Mw	Mass of Water in Filter Paper, g (M1-M2)
38.8504	28.2860	22.6612	20.3513	Wf	Water Content of Filter

					Paper % (Mw/M2)
2.3005	3.1258	3.5617	3.7416	ht	Total Suction, log kpa

MEASUREMENT OF SOIL MATRIC SUCTION USING FILTER PAPER
SAMPLE NAME: RASAFA 1
DATE TESTED: 23-1- 2011 DATE SAMPLE: 16-1-2011

100	90	80	70	Degree of Saturation %	
8	7	6	5	Moisture Tin No.	
Bottom	Bottom	Bottom	Bottom	Bottom Filter Paper (circle) (twofilters)	
0.4693	0.3303	0.3156	0.2929	M1	Mass of Wet Filter Paper, g
0.2294	0.2278	0.2371	0.2382	M2	Mass of Dry Filter Paper, g
0.2399	0.1025	0.0785	0.0547	Mw	Mass of Water in Filter Paper, g (M1-M2)
104.5771	44.9956	33.1084	22.9639	Wf	Water Content of Filter Paper %(Mw/M2)
1.0002	1.8218	2.7478	3.5381	hm	Matric Suction, log kPa

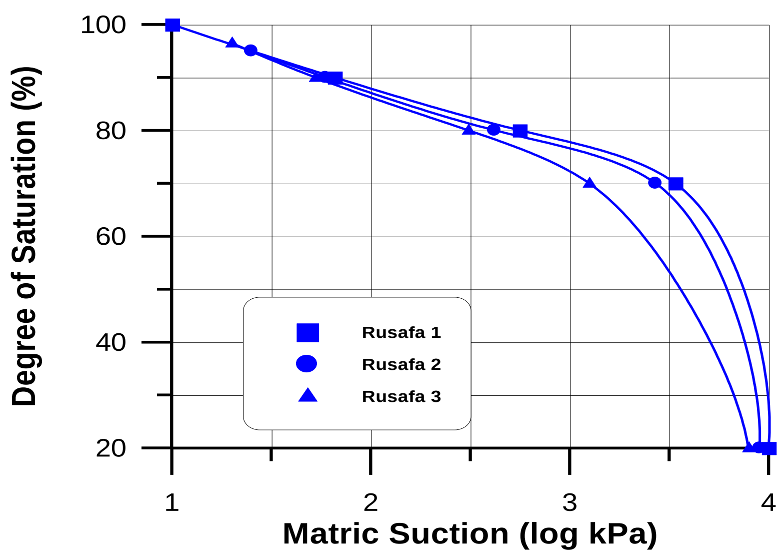


Figure 11**:** Relationship between the matric suction and degree of saturation.

6 H-modulus Function

H is a modulus relating the change of volumetric strain in the soil structure to change in suction. This modulus is required in finite element analyses of unsaturated soil problems [24].

There are sets of steps considered to find the H-modulus function. These steps are proposed in this work in order to characterize the behavior of unsaturated soils:

1. From the program (Soil Vision), which provides fitting of mathematical equations to laboratory data from soil properties, 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 [25] and Van Genuchten [26] for fitting the soil water characteristic curve **(**Figure 12**)**.
2. The previous relations are converted to relations correlating the void ratio and the matric suction based on the relation:

$$e = \frac{W_w G_s}{S} \quad (2)$$

where ww = gravitation water content,
Gs = specific gravity, and
S = degree of saturation.

Then, the slope of the void ratio versus the matric suction, m is predicted:

$$m = \frac{\Delta_e}{\Delta h_m} \quad (3)$$

where: Δe = (e2 – e1), and Δ hm = (hm1-hm2)
hm1, hm2 are the initial and final matric suctions, respectively.
e1, e2 are the initial and final void ratios, respectively.

Hence, seven values of the slope are predicted from these curves.

Figure 13 shows the steps followed to find the slope of the void ratio versus the matric suction (log-scale) relation for different soil types.

3. After finding the slope of the void ratio versus the matric suction relation of different types of the soil, it can be seen that thes slope, m is equal to $\frac{3}{(1-n)H}$ [23]:

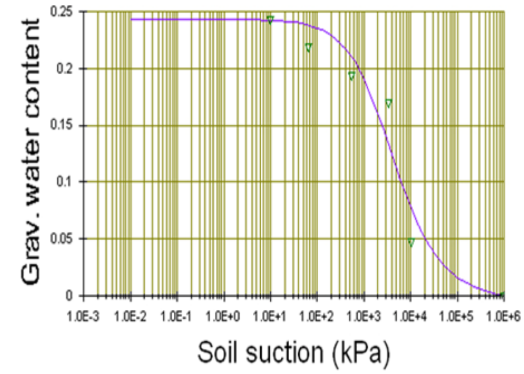
Hence, the H-modulus function becomes:

$$H = \frac{3}{(1-n)m} \quad (4)$$

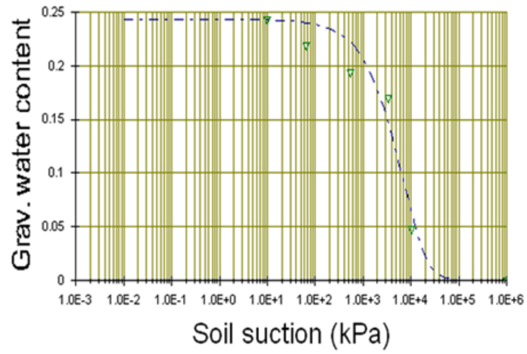
where: n = porosity of soil,
m = the slope of the void ratio versus the matric suction.

In addition, the H must be set to E/ (1-2ν) at zero pore water pressure when defining it [29].

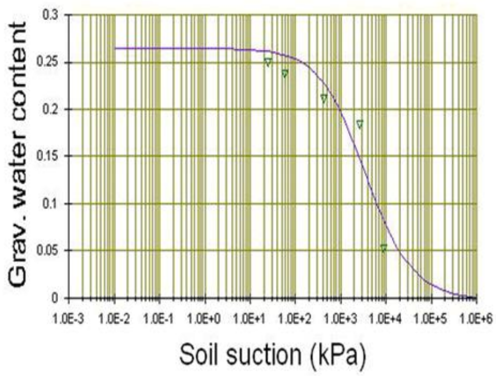
Figure 14 shows the relations between the H – modulus and the matric suction calculated for different types of soil.



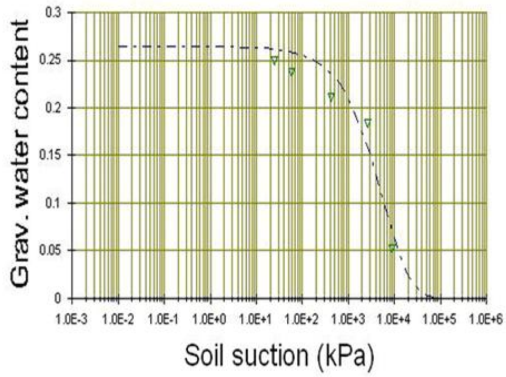
(a) Using Fredlund and Xing [25] fitting for Rasafa 1.



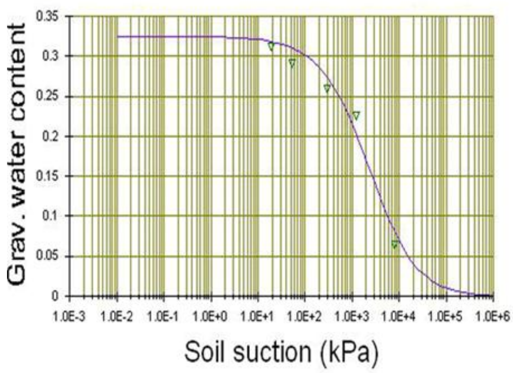
(b) Using Van Genuchten [26] fitting for Rasafa 1.



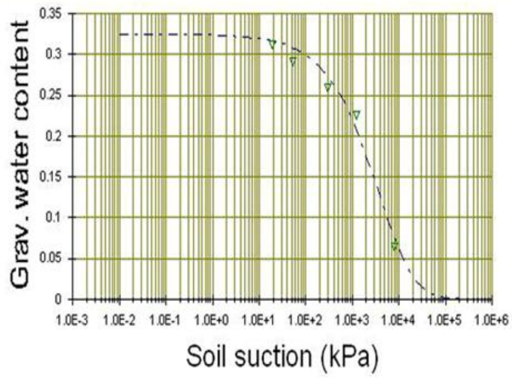
(a) Using Fredlund and Xing [25] fitting for Rasafa 2.



(b) Using Van Genuchten [26] fitting for Rasafa 2.

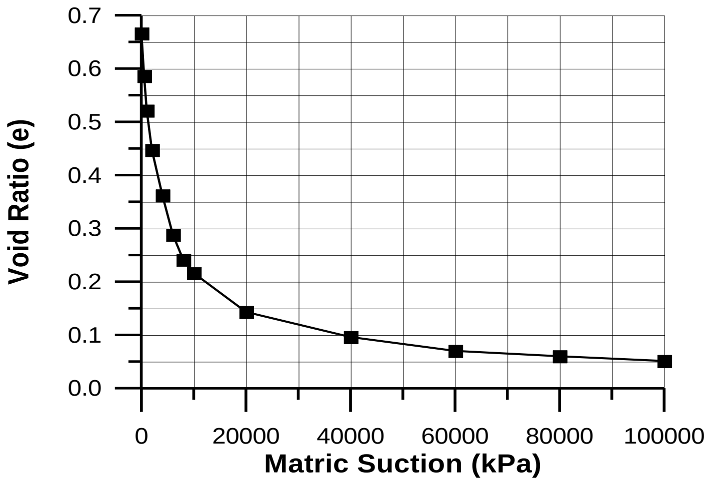


(a) Using Fredlund and Xing [25] fitting for Rasafa 3.

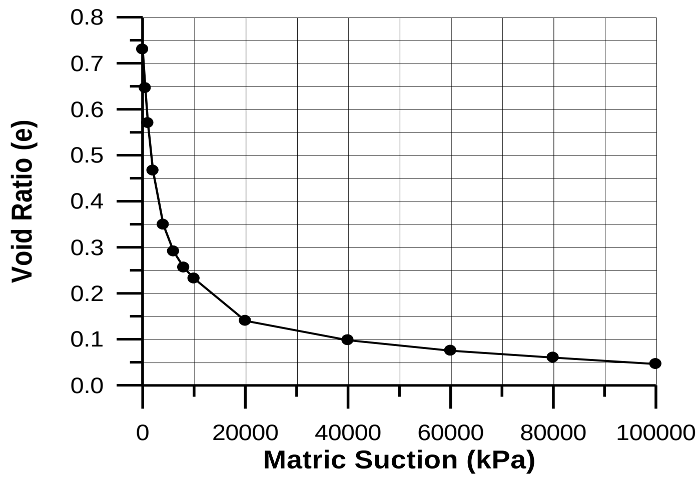


(b) Using Van Genuchten [26] fitting for Rasafa 3.

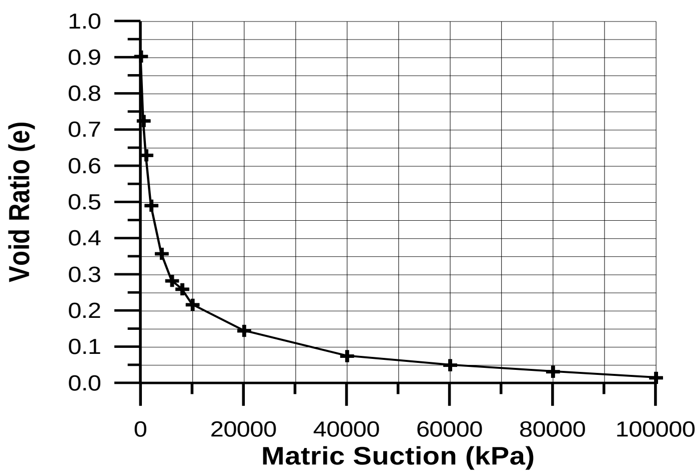
Figure12**:** Relationships between the gravitational water content and the matric suction for different soil types obtained by the program soil Vision.



(a) Rasafa 1 soil.

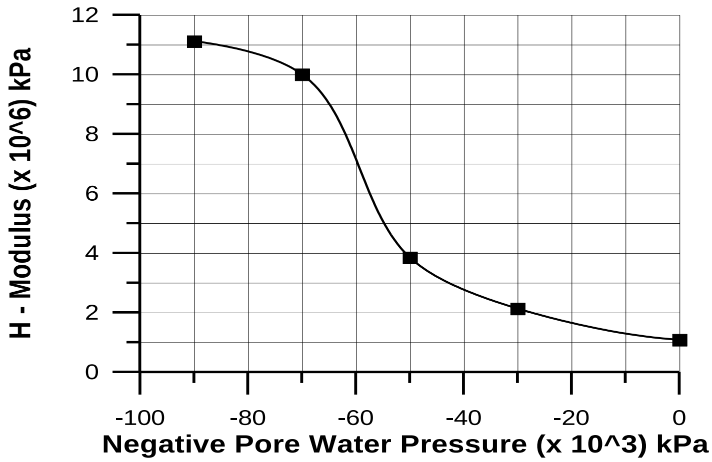


(b) Rasafa 2 soil.

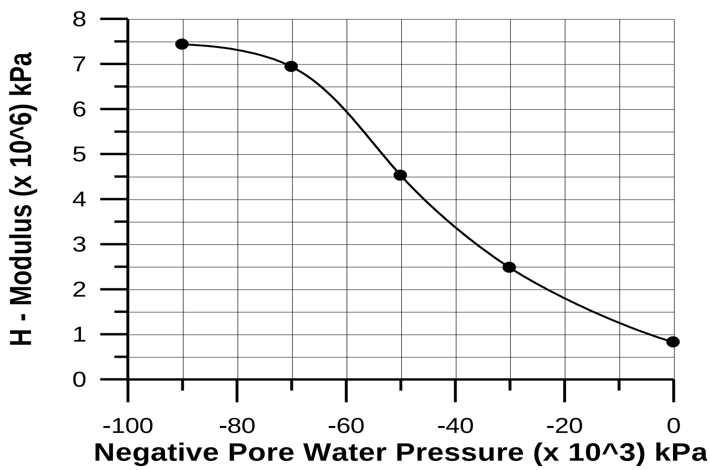


(c) Rasafa 3 soil.

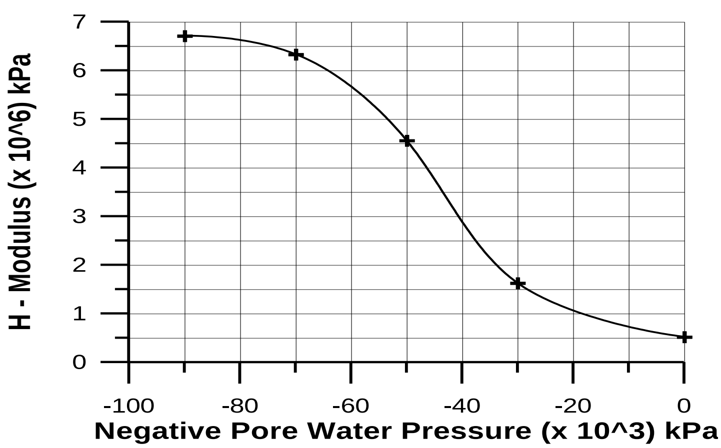
Figure 13**:** Relationships between the void ratio and the matric suction for different soil types using Fredlund and Xing (1994) fitting.



a) Rasafa 1 soil.



b) Rasafa 2 soil.



c) Rasafa 3 soil.

Figure 14**:** Relations between the H-modulus and the matric suction for different soil types.

7 Volumetric Water Content (θw)

In soil science, volumetric water content 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. Frendlund and Rahardjo (1993) [1], defined the volumetric water content as the ratio of volume of water, *Vw*, to the total volume of the soil,

$$\theta_w = \frac{V_w}{V} \tag{5}$$

The volumetric water content can also be expressed in terms of specific gravity, Gs, void ratio, e, and water content as a function of soil suction:

$$\theta_w = \frac{W(h)G_s}{1+e} \tag{6}$$

where *w(h)* = gravimetric water content as a function of matric suction of soil.
The relationship between volumetric water content and pore water pressure can be estimated from input data such as, volumetric water content at saturated condition, θs, and coefficient of volume change, *mv*, and from closed form solution of Van Genuchten [26], or closed form of Fredlund and Xing [25]. The four parameters *a, n, m* and *hr*, in Eqs. (7) and (8) can be obtained from a semilog plot of the soil water characteristic curve.

$$\theta(h,\alpha,n,m) = C(h)\frac{\theta_s}{\left\{\ln\left[e+\left(h/\alpha\right)^n\right]\right\}^m} \tag{7}$$

$$C(h) = \frac{-\ln\left(1+h/h_r\right)}{\ln\left[1+\left(1{,}000{,}000/h_r\right)\right]} + 1 \tag{8}$$

First, the suction corresponding to the residual water content *hr*, is determined by locating a point where the curve starts to drop linearly in the high suction range (Figure 15). Next, the inflection point (*hi*, θ*i*) is located on the semi-log plot and a tangent line is drawn through this point. Then the fitting parameters *a, n,* and *m* can be determined as follows:

$$a=h_i \tag{9}$$

$$m = 3.67\ln\left[\frac{\theta_s C(h_i)}{\theta_i}\right] \tag{10}$$

$$n = \frac{1.31^{m+1}}{mC(h_i)}3.72\,S^* \tag{11}$$

where *θs* = volumetric water content at saturated condition, and
hi = the suction corresponding to infection point.

$$S^* = \frac{S}{\theta_s} - \frac{h_i}{1.31^m(h_i+h_r)\ln\left[1+\left(1{,}000{,}000/h_r\right)\right]}$$

The slope, s, of the tangent line can be calculated as follows:

$$s = \frac{\theta_i}{\ln\left(\frac{h_p}{h_i}\right)} \qquad (12)$$

where *hp* = intercept the tangent line on the semi-log plot and matric suction axis, (Figure 15). In this Figure ψ*i*, and ψp means *hi*, and *hp* respectively.

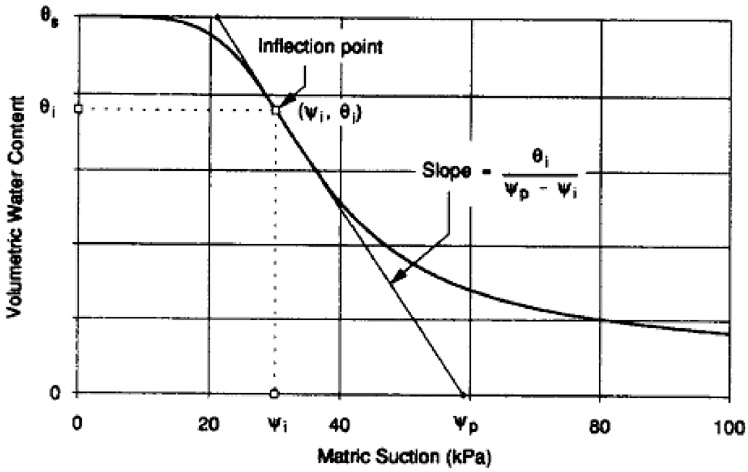
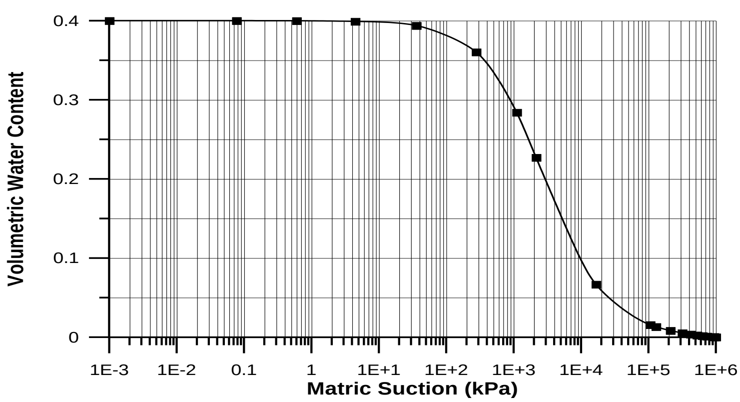
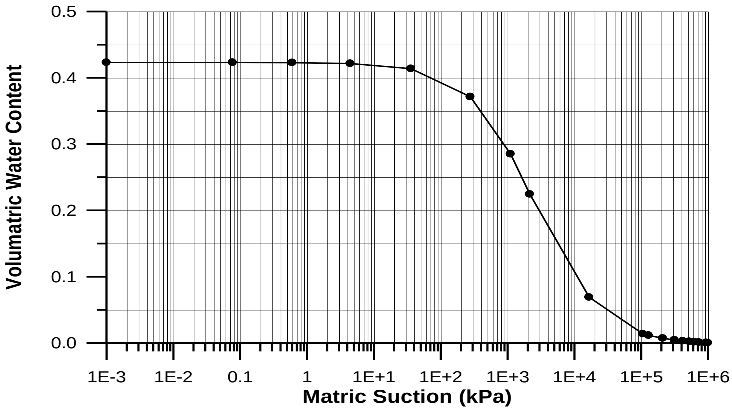


Figure 15**:** A sample plot for the graphical solution of the four parameters (*a*, *n*, *m*, and *h*) (Fredlund and Xing 1994) [25]

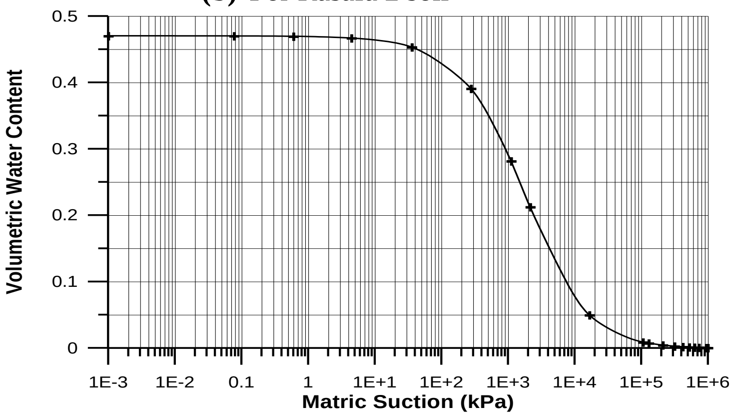
Figure 16 shows the estimated relation between the volumetric water content and matric suction (negative pore water pressure) for the soils. After estimating the relation between the volumetric water content and pore water pressure, a relationship between the hydraulic conductivity and pore water pressure can be estimated. This relation is shown in Figure 17 for the three soils. From the figure, it can be noticed that the soil permeability decreases with increase of the matric suction value for the three soils.



(a) For Rasafa 1 soil

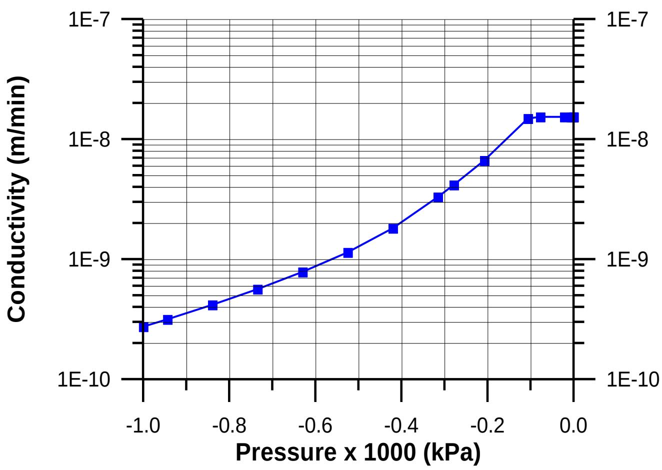


(b) For Rasafa 2 soil

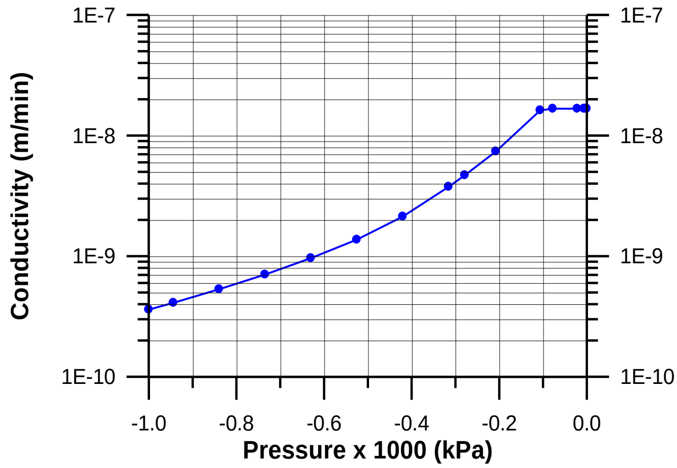


(c) For Rasafa 3 soil

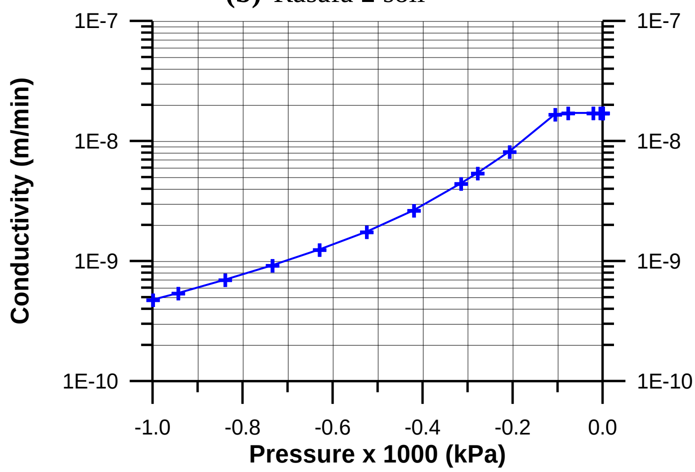
Figure 16: Relationships between volumetric water content and matric suction for the three soils



(a) Rasafa 1 soil.



(b) Rasafa 2 soil



(c) Rasafa 3 soil

Figure 17**:** Relation between the hydraulic conductivity and pore water pressure for partially saturated soils from three sites

8 Conclusions

Based on the experimental results obtained from this research work, the following conclusions can be made:

1. From the soil water characteristic curve (SWCC) which was determined by experimental method (i.e. filter paper method) for three soils; Rasafa 1, Rasafa 2, and Rasafa 3, the matric suction value was found to increase with decrease of the degree of saturation, and the rate of increase is not equal to the rate of decrease in degree of saturation. Also, the values of matric suction increases with decrease of the void ratio at the same degree of saturation.
2. The unconfined compressive strength (qu) increases with the decrease of saturation (S), and consequently increase of undrained shear strength (Cu), while the angle of internal friction (ø) remained constant (i.e. equal to zero). Also, the permeability decreases with increase of the matric suction value.

3. A proposed procedure is presented to define the H – modulus function (H is a modulus relating the change of volumetric strain in the soil structure to change in suction). It depends on predicting the (SWCC) by applying fitting methods with the aid of the program (Soil Vision), after identifying the basic properties of the soil such as Attereberg limits, particle size distribution, void ratio, porosity, and wet and dry unit weights. Then, this relation is converted to relation correlating the void ratio and matric suction. The slope of the latter relation can be used to define the H-modulus function.

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