New Classıficaton and Hydraulic Property Testing for Wet Unsaturated Fine-Graıned Soils

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Abstract
This paper summarizes research study conducted and has two parts. The first part, classifies fine-grained soils with a new method (USCSM) using Laser Diffraction Method to distinguish within fine particle sizes. The second part, determines hydraulic conductivity (k) and volumetric water content (vwc) of 3 selected unsaturated undisturbed soils with a new hydraulic property tester "Hyprop test", using the evaporation method. Results showed that under atmospheric (ie. zero pressure) conditions, matric suction (MS) increases with time upto a maximum value then decreases, when cavitation into soil sample or the measurement system at the air entry value (AEV).Reaching time for the maximum matric suction (MMS) increases with decreasing plasticity index (PI) and colloid content (c). MMS increases with PI, c, while increasing matric suction (MS) decreases hydraulic conductivity (k) and c. Also, k at the MMS decreases with increasing PI and c.

Keywords: *Unified Soil Classification System-Modified (USCSM), unsaturated fine-grained soils, inorganic clay-colloids, soil hydraulic properties, water-retention, hydraulic conductivity, matric suction, laser diffraction method.*

1. INTRODUCTION

Many soils are unsaturated fine-grained soils, existing in high water contents in the wet side of the optimum water content. Before doing any underwater construction activity like; excavation, dredging, offshore structure's foundation piling, seabed ground improvement etc., soils should be first classified and then unsaturated soil's hydraulic properties should be assessed. An uncontaminated unsaturated fine-grained soil may exist in 3 phases. These are: (1) soil gases; (2) soil water; (3) organic and inorganic solids. For a contaminated soil, a 4.th phase called: nonaqueous phase liquids (NAPLs), is added. In this study, only wet uncontaminated unsaturated soils near the optimum water content will be considered for simplicity. As waste constituents may be found in gas, liquid or solid phases, mobile colloids (organic or inorganic, such as; clay colloids) can be suspended in water in the subsurface environment and can play a significant role as carriers of contaminants (Puls et.al. 1991; Burden an Sims 1999).

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2. PART A: CLASSIFYING SOILS BY THE UNIFIED SOIL CLASSIFICATION SYSTEM

2.1 HOW THE EXISTING USCS WORKS

In the geotechnical engineering practice, the Unified Soil Classification System (USCS) is a widely used classification system worldwide as described in Table 1 (USAE-WES:TM3-357 1960).

Table 1. *Particle size ranges of the USCS (USAE-WES:TM3-357 1960).*

The Unified Soils Classification System (USCS)	
Particle	Size Range(mm)
Cobbles	>76.2
Gravel	4.76-76.2
-Coarse	19.1-76.2
-Fine	4.76-19.1
Sand	0.074-4.76
-Very Coarse	-
Coarse	2.0-4.76
-Medium	0.42-2.0
-Fine	0.074-0.42
-Very Fine	-
Fines*(silt and clay)	<0.074
Clay	<0.002
(*) Note: USCS silt and clay designations are determined by response of the soil to manipulation at various water contents, rather than by measurement of particle size.	

The analytical procedure to obtain soil fractions is called particle-size analysis. Sieves are used to separate very fine sand and larger particles (ASTM D 421-07 and D 422-07e1). Silt and clay contents are determined by measuring the suspention settlement rate separates in water by the hydrometer test (ASTM D 422-07e1). In the USCS, silt and clay contents are determined by soil behavior various water contents by using soil plasticity chart (ASTM D 4318-10e1)(Fig.1), rather than soil particle size measurement. Thus, the USCS does not distinguish silts, clays, colloids, which are called as "fines"(ASTM D 2487-11).

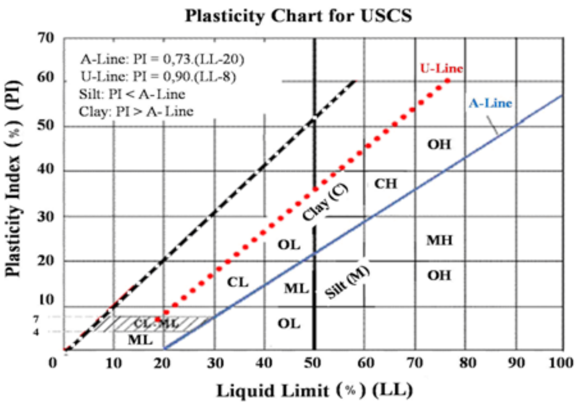
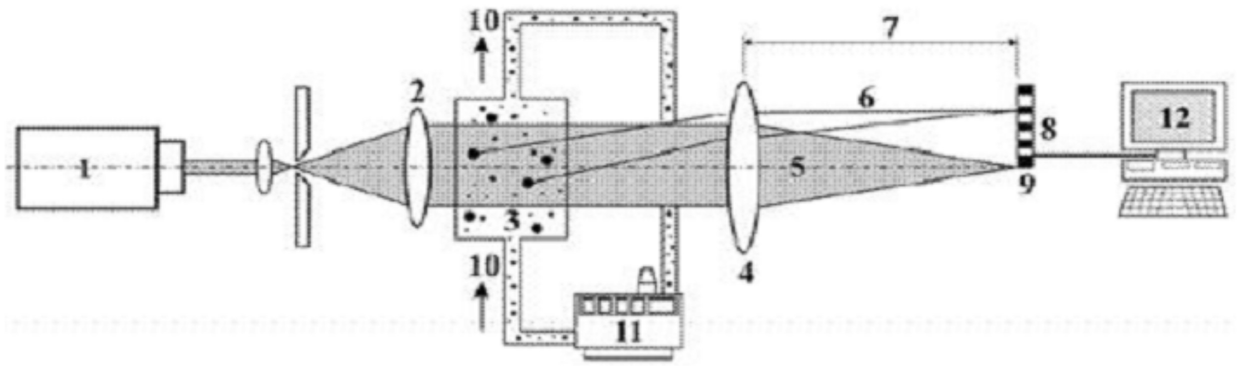


Fig. 1. *Soil Plasticity Chart of the USCS (ASTM D 2487-11).*

Colloids are commonly defined as mean particles or macromolecules smaller than 1µm in diameter but larger than 1nm (Puls et.al. 1991; Burden and Sims 1999). A.W. Skempton of Imperial College , who has already reported some colloidal activity of clays (Skempton 1953).

For fine grained soils having particle sizes of upto 2x0.001mm, particle size distributions can be determined by the hydrometer analysis. This is almost the limit for a normal microscope. But, between 2x0.001mm.and 0.000001mm (10Aº) particle sizes, electron microscopes or laser diffraction method is used, where for the latter, test set-up is as shown in Fig. 2 (Ozer 2006; Ozer et.al. 2009).



Notes: 1.laser source, 2.Beam expander, 3.Sample cell, 4.Fourier lens, 5.Non-scattered laser beam, 6.Scatteed laser beam, 7.Len's focal distance, 8.Multi-element detector, 9.Obscuration detector, 10.Flow direction of suspension, 11.Sample unit, 12.PC.

***Fig.2**. General Set-up of the Laser-Diffraction instrument used for d istinguishing colloid size (Ozer 2006).*

2.2. SIZE-DISTINCTION MADE IN THE EXISTING USCS WITHIN FINE-GRAINED SOILS

Using the USCS have encountered many ambiguities among practising geotechnical engineers in defining the fine grained soils (eg. silts, clays and particles finer than clay size), just based on their plasticity properties. Hence, the USCS remained for a long time as a less precise method of classification for fine grained soils, considering the particle size determinations. This is because the USCS doesn't make any distinction between the silt and clay sizes, except indicating that the soil is "silt", if liquid limit is between 25.5% and 100% (ie. 25.5<LL<100%), provided that the plasticity index is below the A-line (ie. PI<A-Line). On the other hand, the soil is "clay", if the plasticity index is between the A-Line and the U-Line (ie. A-Line<PI<U-Line) (USAE-WES:TM3-357 1960). Other main shortcomings of the USCS are;

- The USCS doesn't well-define soil classification, if the PI of the soil is higher than the U-Line.
- The distinction between silty-clay(CL-ML) and clayey-silt (ML-CL), for the same PI, is not clear.
- The USCS doesn't subdivide any clay size, so that its particle size distribution can be related to the existence of any risk for soils' dispersive, expansive or contaminant-carrying properties.
- When PI is below the A-line with LL<50%, soil is silt; but above the A-line with LL<50% soil is clay, in which for both cases the distinction between ML (silt) and OL (organic clay or organic silt) is not clearly made. The same is also true for the OL itself, which can represent 2 different varieties of such soils.
- If PI is below the A-line and LL>50%, the distinction between MH (elastic silt) and OH (organic clay or organic silt) is not clearly made. The same is also true for the OH itself, which can represent 2 different varieties of such soils.
- Hydrometer test (using Stokes Law) overestimates microfines, where particle size < 0.002mm, compared to the lazer diffraction analysis (Ozer 2006; Ozer et.al. 2009; Wen et.al. 2002).

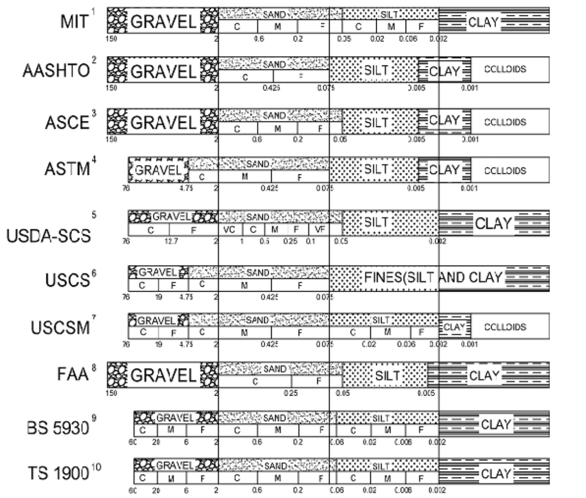
These classification uncertainities for the fine grained soils could be greatly reduced, by incorporating their recommended particle sizes into the classification system as in Table 2.

Table 2. *Recommended particle sizes of the fine-grained soils in the new USCSM (Sahin 2013).*

Fine-grained soil's Particle Type		Particle Size Range (mm)
Main Group	Fraction	
Silt	Coarse	0.076 – 0.02
	Medium	0.02 – 0.006
	Fine	0.006 – 0.002
Clay	-	0.002 – 0.001
Colloids	-	0.001-0.000001 mm (or 1000-1 nm).

In order to better define the classification size sublimits for the fine grained part of the USCS, distinction is made (between the sizes of silt, clay and colloids) in the new clasification system, which is called: "The modified USCS or USCSM, where the term "M" stands for the word "modified". It's noted that (inorganic) clay colloids are very fine particles having particle sizes between 0.001-0.000001mm (or 1000-1 nm) (Puls et.al. 1991; Burden and Sims 1999).

Comparison of the new USCSM, with some other major soil classification systems is shown in Fig. 3.



Notes:

(1) **MIT**: Massachusetts Institute of Technology's-Soil Classification System (Lambe, 1979).

(2) **AASHTO**: American Assoc. of State Hwy. & Transp.Officials' - Soil Class.Sys.(AASHTO-MSI, 1988).

(3) **ASCE**: American Society of Civil Engineers'-Soil Classification System (ASCE-STP, 1978).

(4) **ASTM**: American Society for Testing and Materials'-Soil Classification System (ASTM D 2487).

(5) **USDA-SCS**: US Department of Agriculture's-Soil Classification System (Burden and Sims, 1999).

(6) **USCS**: The Unified Soil Classification System (USAE-WES:TM3-357, 1960).

(7) **USCSM**: The Unified Soil Classification System-Modified [as proposed] (Sahin, 2013).

(8) **FAA**: The US Federal Aviation Administrations' -Soil Classification System (NAVFAC DM 7.1, 1982).

(9) **BS**: British Standards Instute's-Soil Classification System (BS 5930, 1981).

(10) **TS**: The Turkish Standards Institute's- Soil Classification System (TS 1900-2, 2006).

Fig. 3. *Comparison of particle sizes (mm) for some major soil classification systems (Sahin 2013).*

3. PART B: TESTING WET UNSATURATED FINE-GRAINED SOILS FOR HYDRAULIC PROPERTIES

3.1 DEFINITION OF WET UNSATURATED FINE GRAINED SOILS

The term: "Wet Unsaturated Fine-Grained Soils" refers to wet unsaturated fine-grained soils, which belong to wet side of the "Optimum Water Content, determined by the standard (ASTM D 698-12e1) or (ASTM D 1557-12). This range is near saturation, whereby the air phase exist as either in occluded air bubles or as dissolved air in water (Egeli 1981; Egeli 1992), rather than the broad range of unsaturated soils on the dry side, whereby existence of "contractile skins" touching soil particles occur and these also cause pressure differences to exist between the discontinuous air and water phases in such pockets. Contractile skin, if exists, is in tension and exerts pulling force on the soil particles, complicates the unsaturated soil behaviour (Fredlund and Rahardjo 1993). Hence, by selecting the wet side of unsaturated fine-grained (UFG) soils, where water phase is continuous and hydraulic property behaviour is better understandable, compared to unsaturated soils' behaviour on the dry side.

4.1 Suction and Hydraulic Conductivity Measurements' Review in UFG Soils

Soil suction is an important parameter to describe moisture condition in engineering behavior of unsaturated soils. Soil suction is expressed as a pressure term, which shows pulling force (tension) exerted on the water. Matric suction is the diffeence between air pressure and pore water pressure. Total suction is the sum of the matric and osmotic suctions (Snethen 1980; Fredlund and Rahardjo 1993). Matric suction controls shear strength and hydraulic conductivity of an unsaturated soil (Cokca and Tilgen 2010; Pan et.al. 2010). Also, matric suction is related to capilarity, mineral structure and adsorptive surface forces (Deka et.al. 1995). On the other hand, pore fluid osmotic suction is related to the dissolved salt content in pore water and affects swelling properties, yet it is independent from the water content having the same ion-concentration (Bulut et.al. 2001; Rao and Shivananda 2005). Thus, rather than total suction, matric suction is a significant parameter to use in engineering practice to predict the behaviour of an unsaturated soil (Fredlund and Rahardjo 1993; Burden and Sims 1999). Though Filter paper method is a simple indirect technique for measuring total and matric suctions (Houston et.al. 1884; Deka et.al. 1995; Bulut et.al. 2001; Pan et.al. 2010), tensiometers are the quickest, the most practical and giving more accurate results for measuring matric suctions (Houston et.al. 1994; Deka et.al. 1995). In this study we've used tensiometers (Hyprop:11/2010 2012). Also, matric suction is an important parameter, both for determining water-holding capacity and engineering behavior of unsaturated soils (Cokca and Tilgen 2010). Although factors for the soil suction changes are important, the aim here is to determine how matric suction and other basic soil properties affect control unsaturated fine-grained soils' hydraulic properties, such as; the maximum water-retention capacity and the maximum hydraulic conductivity capacity, especially for clays with low (<10%) to medium (10-30%) colloid contents. This is because of the fact that such ranges are commonly encountered in practice in clays having colloids.

4.2 Hyprop Testing for UFG soil's Water-Retention and Hydraulic Conductivity Properties

Before it was known that; hydraulic conductivity of an unsaturated soil decreases, while an unsaturated soil's matric suction increases (Rao and Shivananda 2005; Agus et.al. 2003).

Although there are several indirect matric suction measurement methods in laboratory (e.g. time domain reflectometry, electrical and thermal conductivity sensors, in-contact filter paper technique etc.), direct suction measurement methods in laboratory (e.g. axis-translation technique, suction probes, tensiometers etc.) are commonly used by the practitioners, particularly the last one being the most common (Pan, et.al. 2010). Yet, validity of assumptions and reliability of measurements in each method should be carefully checked, when assessing the results, as some assumes continuous pore air phase (good for dry side of the optimum water content) or continuous pore water phase with air is in bubbles, or probes may not qualify for making continuous measurements from small (few kPA) to medium (100 kPa) and to very high range (1000 kPa) of matric suctions, covering a wide range from full saturation to drying. In engineering practice, the first two rangers are the most important range for practical, purposes and they can be read by tensiometers. By selecting the wet unsaturated soil samples studying is narrowed to the wet side of the optimum water content, where water phase is continuous having air in bubbles and starting from sample's full saturation (S=1) stage with using slow evaporation process at room temperature inside laboratory, good reliability with tensiometer measurements can be obtained. This approach was used in the below described new method to measure wet unsaturated soil's hydraulic properties, including water retention and hydraulic conductivity. This recently developed equipment is called Hyprop (Hydraulic Property Analyzer, or Hyprop:11/2010 2012, in short), which covers 0-100 kPa matric suction measurement range and uses the evaporation method (Peters and Durner 2008; Schindler et.al. 2010). Plotted results are given below.

4.2.1 Sample preparation: Before testing, the protective cap of the sample (the side with the straight rim without cutting edge) is removed and the undisturbed sample is extruded from the "Shelby-Tube" by the sampler ring and mesh fabric is placed on the sample. Then the perforated attachment cap and clamp is attached to the sample. Dish is filled with de-aired/de-ionised water, before sample is placed with the perforated attachment for reaching full saturation. The water level should be 1 cm below the upper rim of the sampling ring. The provided sampler-ring's cutting edge shows upward, thus the sample is made saturated (above those for the undisturbed "Shelby-Tube" saturation degree values shown in Table 5 until S=1 for all) from the sampler-ring's reverse side (Fig. 4).

Fig. 4. *Dish with water and the soil sample is allowed to reach saturation in the stage (Sahin 2013).*

Then the set-up continues with degassing of the tensiometers and the sensor unit. To achieve this, the ceramic tip is inserted into the tube with the ceramic tip pointing downwards toward the syringe. The tip should be close to the syringe's nozzle. Then, the syringe is pulled upright to get rid of all air bubbles in the syringe and in the ceramic tip. Degassing the sensor unit is critically importance and needs to be done first with delicate handling. After, the acrylic caps are attachment onto the sensor heads, following the filling-up the acrylic attachment with de-aired/de-ionised water using the droplet syringe. When the tensiometers are filled with de-aired water, they are placed onto the sensor unit with silicone caps on, which is then inserted into the sample. Its' noted that care must be placed not to exceed 1 bar pressure to avoid soil disturbance. After, then the soil sample is taken out of the dish and is placed on the sensor unit assembly (Fig. 5).

Fig. 5. *Assembling the Hyprop Sensor Unit with the coring sampler-ring (Sahin 2013).*

Next step is to place the silicone disk over the tensiometers and to close the clips to fix the sampling ring and the sensor unit to make a tightly-clad assembly. Then placing the assembly unit onto the weighing scale starts the evaporation method (Peter and Durner 2006, 2008; Schindler et.al. 2010) (Fig.s 6-8).

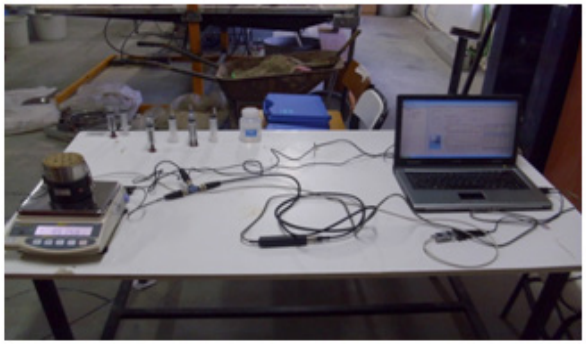


Fig. 7. *Experimental set-up of the Hyprop tests (Sahin 2013).*

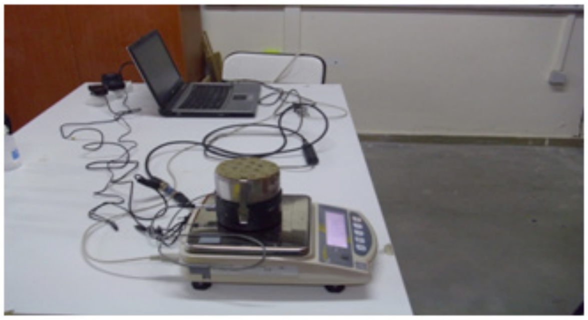


Fig. 8. *A Hyprop test is in progress (Sahin 2013).*

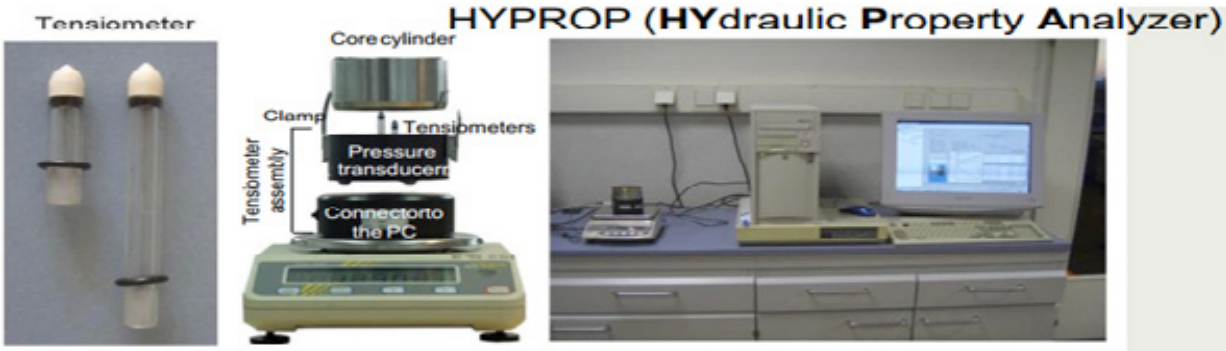


Fig. 6. *General view of the Hyprop test set-up (Sahin 2013).*

4.2.2 Hyprop Testing Theory using the Evaporation Method: Soil sampling ring has two tensiometers, which are installed in a soil sample at two depths (z1 and z2). The middle point between the tips of the tensiometers should correspond to the centre of the soil sample. To begin with the testing progress the undisturbed soil sample is obtained by slowly pushing-in of coring cylinder into the "Shelby-Tube". This sub-sample so obtained, is made saturated before the test starts by placing its closed side on the Hyprop scale. The upper side of the sample is open to atmosphere inside the laboratuary so that soil can loose moisture by slow evaporation at the constant laboratory temperature (with no fast blowing winds/air currrents in the laboratory, which hinder results due to allowing fast evaporation to occur).While soil sample's degree of saturation reduces from full saturation (S=1) by loosing moisture thru' evaporation, the soil water tension [kPa] causing an average matric suction. Thus the hydraulic gradient is automatically calculated at the mid-point of the sample by using linear regression. The mass difference, measured by the scale, is used to calculate the volumetric water content and the water's flow rate. Measuring process starts automatically, when the sampler ring is placed onto the scale and it lasts until one of the tensiometers runs dry or the mass changes become marginal (nearly zero). The remaining final moisture content is then determined by the oven drying the sample at 105°C for 24 hours. With these values the retention curve and the unsaturated conductivity is found by intermittent points [upto (-)100 kPa] and beyond [upto (-) 1000 kPa] by the built-in software's extrapolation program.

Discrete Data for Retention and Conductivity Relation: At different points of time t^i the water tensions $(h_1)^i$ and $(h_2)^i$ (in hPa) of both depths are measured as well as the weight of the sample (in grams). The analytic procedure is based on the assumption that water tension and water content distribute linearly through the column, and that water tension and sample weight changes are also linear between the two evaluation points. The initial water content is determined from the total loss of water (i.e. by evaporation+water loss by oven drying).The average water content (θ^i) is derived from the initial water content and the water loss by weight. Thus the medial water tension h^i give a discrete value ($\theta^i(h^i)$) of the retention function at any time t^i.

For the calculation of the conductivity function, it is assumed that between the two time points $t^{i-1}$and t^i the water flow through the cross section situated exactly between both tensiometers (and therefore exactly at the column centre $q^i=1/2(\Delta V^i/\Delta t^i A)$.$\Delta V^i$ is the water loss in cm^3 determined by weight changes,Δt^i is the interval between two evaluation points, and A the cross section area (in cm^2) of the column. The data for the hydraulic conductivity function are determined by using the Darcy-Equation:

$$K^i(h^i)'' = -(q^i)/(\Delta h^i /\Delta z+1) \qquad (1)$$

Where;

$(h^i)'' = (1/4)[(h^{i-1})_1+(h^{i-1})_2+(h^i)_1+(h^i)_2]$ is the medial water tension between watwo evaluation points, with K^i as the related hydraulic conductivity (in cm h^{-1}).

$\Delta h^i = (1/2)[(h^{i-1})_2-(h^{i-1})_1+(h^i)_2-(h^i)_1]$ is the medial difference of the water tension between the two tensiometers, while $\Delta z = z_2-z_1$ is the distance between both tensiometers (in cm).

K(h) data sets close to saturation are reduce, depending to the accuracy of the tensiometers. To get sufficient number of data points for the hydraulic conductivity function with relatively long intervals,both the tension curve and the weight curve between two evaluation points are interpolated (with hermitian splines) (Van Genuchten 1980). On this basis relatively short evaluation intervals are achieved.

Retention and Conductivity Functions: Normally hydraulic characteristics are described by parametric functions for θ(h) and K(h). In using the Hyprop:11/2010 2012, three analysis models can be chosen. These models can be adapted to measure data via a robust and non-linear optimizing procedure. The Van Genuchten/Mualem model (Van Genuchten 1980) was chosen to determine the hydraulic properties of testing materials in the Hyprop equipment used this study.

Van Genuchten-Mualem Model: With this model the effective saturation $S_e = (\theta-\theta_r)/(\theta_s-\theta_r)$ and the unsaturated hydraulic conductivity, K in relation to the matric potential h are predetermined by the following formulas (Van Genuchten 1980);

$$S_e(h) = (1+(\alpha|h|)^n)^{1/(n-1} \qquad (2)$$

$$K(h)=K_s(1+(\alpha|h|)^n)^{\tau\,(1/(n-1))}[1-(\alpha|h|)^{n-1}[1+(\alpha|h|)^n]^{1/(n-1)}]^2 \qquad (3)$$

Where;
α (cm-^{1}) = Air entry value (AEV).
n (-) = Fitting parameter of the water retention function.

τ = Tortuosity parameter.

In the above equations (1-3), the residual water content is (θ_r) the water content at saturation is (θ_s) the inverse value of the bubble point potential is α [cm^{-1}] and the pore size distribution is n (-) are the fitting parameters for the retention function. Furthermore, the tortuosity parameter, τ (-) and the saturated conductivity, K_s are fitted to get the conductivity function.

Optimization of the Parameters: The θ(h) and K(h) functions are adapted simultaneously to the data points by the built-in softare. Adaption is accomplished by a non-linear regression. However, the assumption that the water content is spread out linearly over the soil column is not always fulfilled in the coarse pored or structured soil samples. Therefore, the so called ‘’integral fit’’applied to adapt the water retention function to overcomes such problems (Peters and Durner 2006; Hyprop:11/2010 2012).

4.2.3 Testing Materials and the methods used: Firstly, it’s noted that this original research work was conducted as part of the MSc Thesis (Sahin 2013), during which study most laboratory work has been carried out at the Geotechnics Laboratory of the Civil Engineering Department at the Izmir Institute of Technology in Urla-Izmir, Turkey. Hence the thesis contains all the tests results summarized here.
This second part of the paper summarizes test results of the above mentioned thesis study, which contains laboratory tests done on locally provided undisturbed ‘Shelby-Tube’ soil samples’ obtained in the field from the nearby Tahtalı Lake’s bottom sediments in Izmir by coring method and their three (3) unsaturated fine-grained (UFG) soil sub-samples, also obtained by using the coring sampling ring (Fig.5) were used. All sub-samples were wetter than their optimum moisture contents and were near to their full saturation (S=1), but with varying degrees of Plasticity Indices (PI, %) and Colloid Contents(c, %). The soil types of these samples using the existing USCS and the new USCSM classifications were ML, OL and CH types. Some laboratory index tests of the used samples were done at the Ege Zemin and İYTE Lab.s in Izmir and the Laser-Diffraction Tests (LDT) were done at the Gazi University-Technical Education Faculty’s-Geotechnical Lab.in Ankara, where the same regression

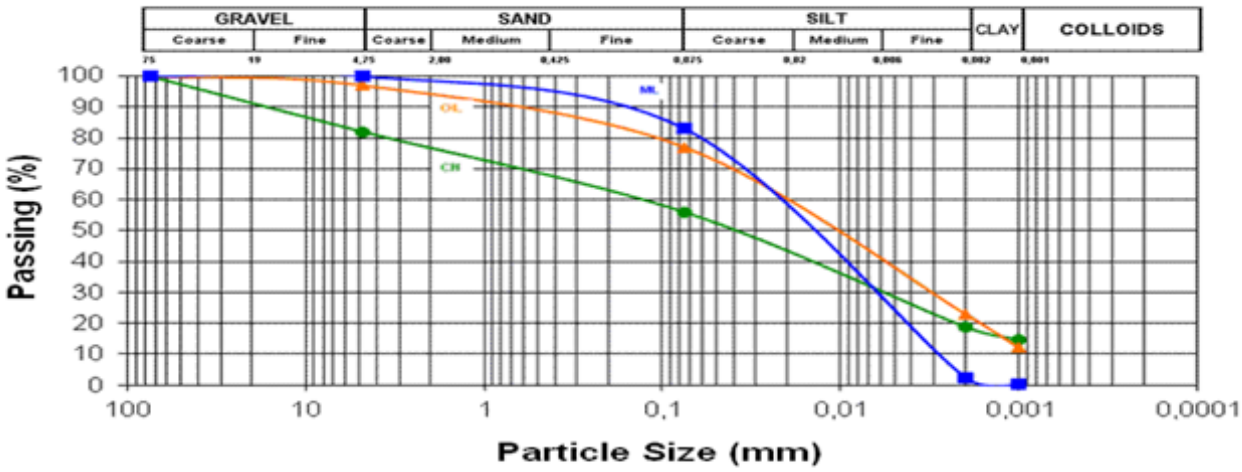


Fig. 9. *PSD graphs of the 3 undisturbed soil samples used in the Hyprop tests (Sahin 2013).*

Table 3. *Comparing lab.test results of 3 undisturbed soil samples tested by the Hyprop set (Sahin 2013).*

Soil Type (By: USCS)	w_i (%)	SG -	Si (%)	e_i -	LL (%)	PL (%)	PI (%)	Sieve Analysis (%)			Hydrometer Analysis (%)		Lazer Diffraction Analysis (%)		Hydraulic Conductivity (mm/day)
								<0.076 (mm)	Sand Size	Gravel Size	<0.0076 (mm)	<0.002 (mm)	<0.002 (mm)	<0.001 (mm)	
CH	29	2.76	91	0.88	52	22	30	56	26	18	56	31	18.8	14.7	0.02818
OL	31	2.72	93	0.91	45	25	20	77	20	3	77	38	23.0	12.0	0.001
ML	32	2.69	94	0.92	33	28	5	83	17	0	83	4	2.4	0.1	0.0631

equation and correlation coefficient was used in using the same testing instrument used with the one used in the original PhD Thesis study conducted there, regarding soils' fine particles passing both of 0.002mm and 0.001mm sieve sizes (Ozer 2006). Particle Size Distribution (PSD) graphs of the 3 undisturbed soil samples tested are shown in Fig.9 and test results are given Table 3. It's noted that; all the soil sample index tests were conducted using the ASTM standards, including the one for the Shrinkage Limit (SL) and Shrinkage Index (SI) tests. Shrinkage Limit (SL) is the % (by weight) water content where further loss of moisture will not result in any volume reduction, but increase in moisture causes a volume increase. SL represents the minimum (gravimetric) water content at which soil can be in saturated condition (Sahin 2013).

It can be seen that Laser Diffraction test gives about 60% lower results content to the hydrometer test. This may be interpreted as the hydrometer test overestimating the fines in suspension by about 40 % (ie for the -0.002mm of the fine fraction). This is due to the fact that the hydrometer theory is derived from the sedimentation theory, which depends on the Stokes law, which may give only approximate results (Ozer 2006; Ozer et.al. 2009; Wen et.al. 2002). Laser Difraction method can also be used to determine -0.001mm of the fine fraction, which shows the % finer than the maximum colloid size of 0.001mm. However, the hydraulic conductivity values reported in Table 3 are the values corresponding to the 3 undisturbed (CH, OL, ML type) sample's maximum matric suction points, as obtained in the Hyprop tests conducted. Results are shown in Fig.s 10-18 below.

4.2.4 Hyprop Test Results:

From the performed tests following results were obtained.

Matric Suction versus Time: For all the 3 samples, matric suction continued to increase gradually over time upto a maximum point (in both variations of the 2 tensiometers showing soil sample's top and bottom tensions), after which it decreased also gradually. Decreasing values show air-entry thru' the seramic tips of probes and should be disregarded. But values upto the first maximum matric suction (MMS) point are correct and can be correlated with the soil sample's index properties (Fig.s 10-12).

ML soil sample

CH soil sample

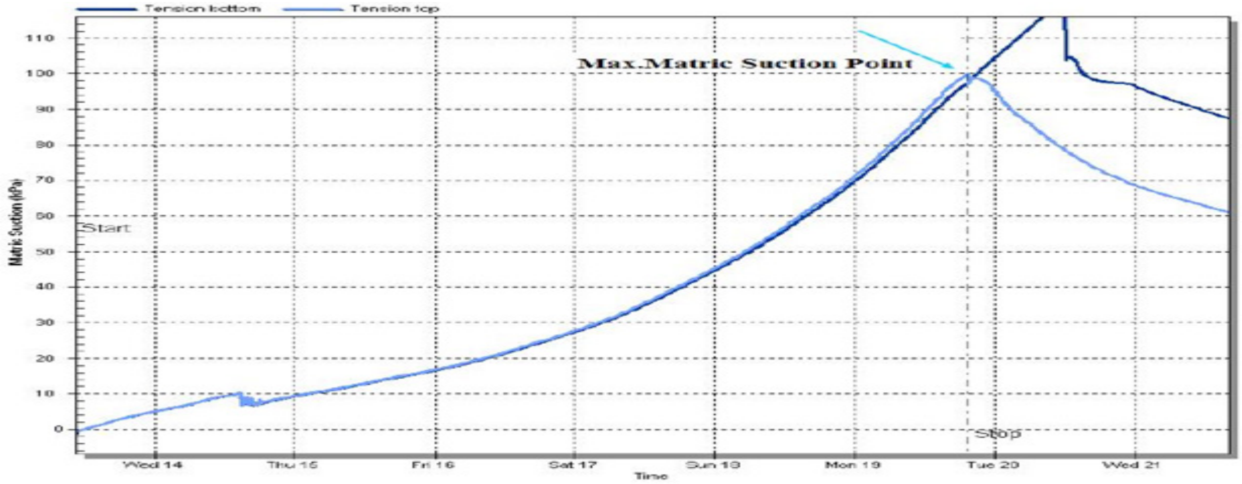


Fig. 10. *Variation of Matric Suction with Time (days) for the ML soil sample (Sahin 2013).*

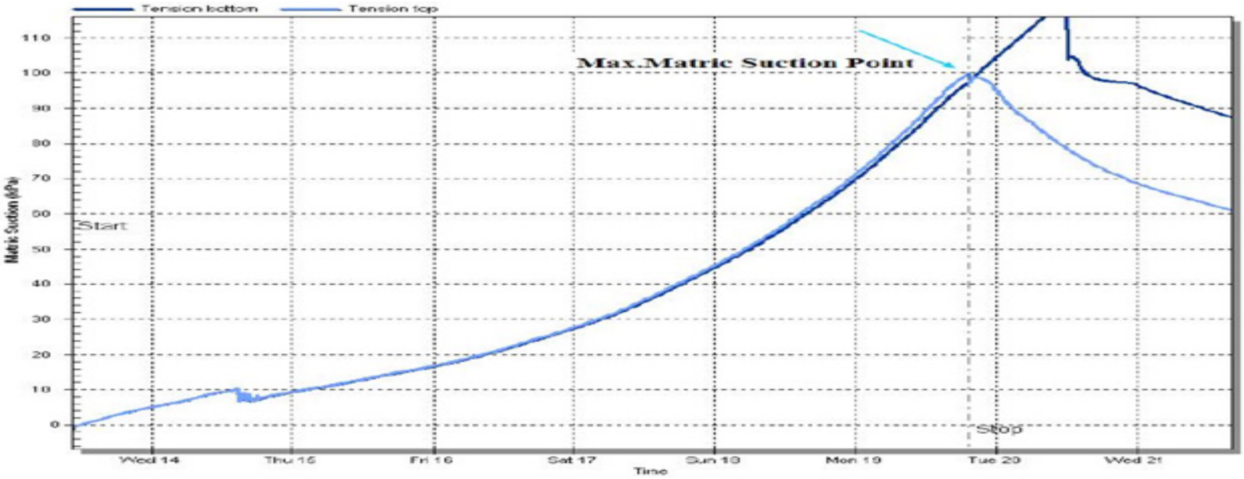


Fig. 11. *Variation of Matric Suction with Time (days) for the CH soil sample (Sahin 2013).*

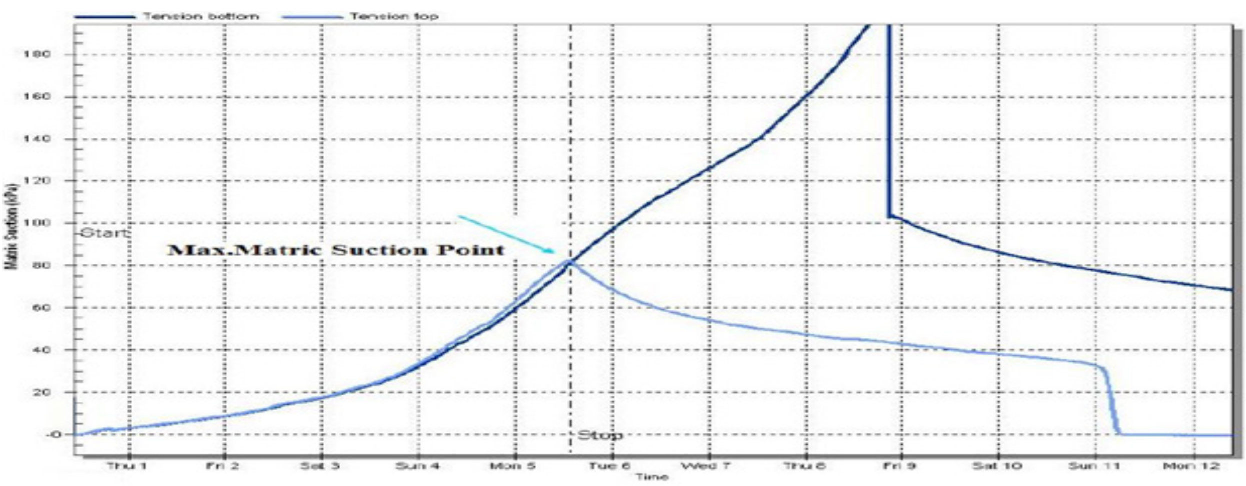


Fig. 12. *Variation of Matric Suction with Time (days) for the OL soil sample (Sahin 2013).*

OLsoil sample

Hydraulic Conductivity versus Matric Suction: Results show that with increasing matric suction, hydraulic conductivity gradually decreased with slow rate upto (-)10 kPa, after which it decreased almost linearly at constant rate upto about (-) 100 kPa. The actual automatic readings at small time intervals by the Hyprop tensiometers are shown in faint bubbles upto about (-)100kPa. Dark line is the result of automatic curve fitting process by the built-in Hyprop software (Fig.s 13-15).

ML soil sample

CH soil sample

OL soil sample

Volumetric Water Content versus Matric Suction: The initial water contents of the sub-samples obtained from the 'Shelby-Tube' is determined by the oven drying method, before the Hyprop tests (Table 5). Weighing scale uses this value as an input and calculates the volumetric value at each automatic measurement, thru' its weighing scale,

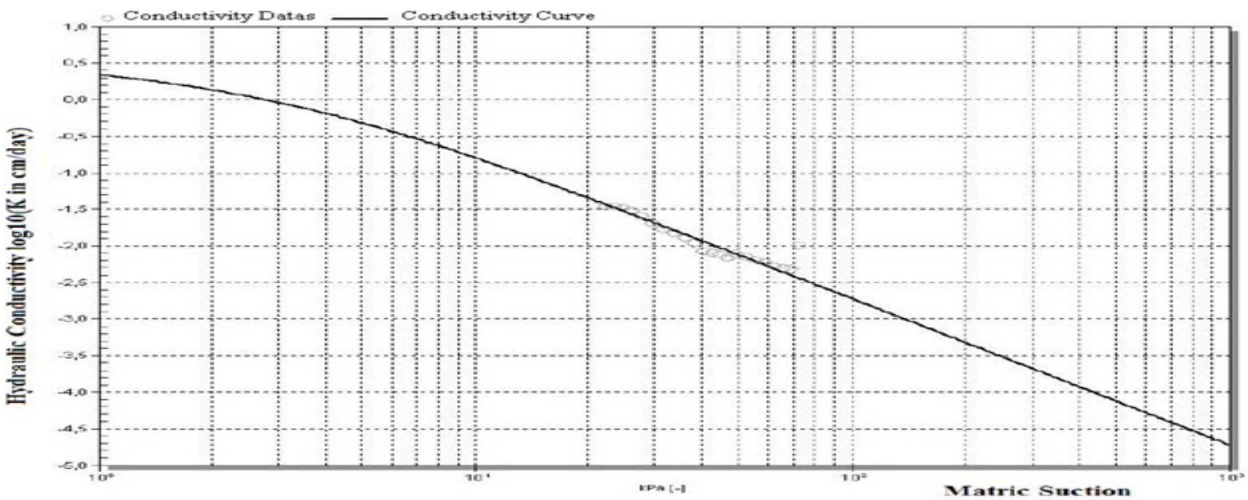


Fig. 13. *Variation of Hydraulic Conductivity with Matric Suction for the ML soil sample (Sahin 2013).*

Fig. 14. Variation of Hydraulic Conductivity with Matric Suction for the CH soil sample (Sahin 2013).

considering the Hyprop assembly is nearly saturated where the known quatities are the sample volume with sensor assembly weight, which is automatically contiounsly calculated by the built-in software. As the method considers only the capillary water filling all the soil pores with no adsorbed (or film) water, the calculated porosity (or void ratio) becomes equal to the saturated water content θ_s and this results during the test are only approximate values. Hence, the water content is called the volumetric water content. Results show that with increasing matric suction, volumetric water content gradually decreases with slow rate upto (-)10 kPa, after which it decreases almost linearly at a constant rate upto about (-) 100 kPa. The actual automatic readings are done at small time intervals by the Hyprop tensiometers as shown in faint bubbles. Dark line is the result of automatic curve fitting process by the built-in Hyprop software (Fig.s 16-18).

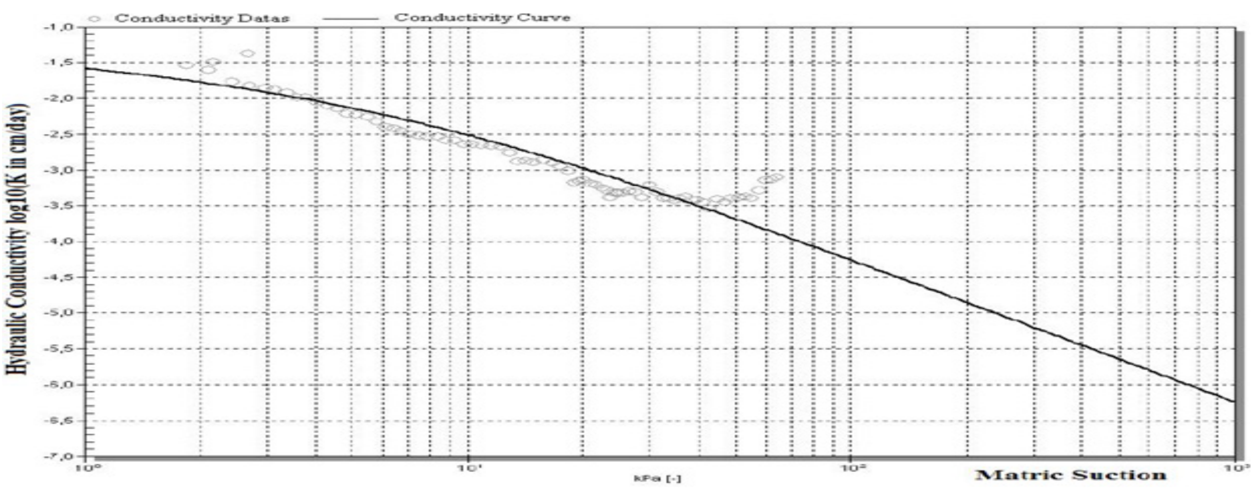


Fig. 15. Variation of Hydraulic Conductivity with Matric Suction for the OL soil sample (Sahin 2013).

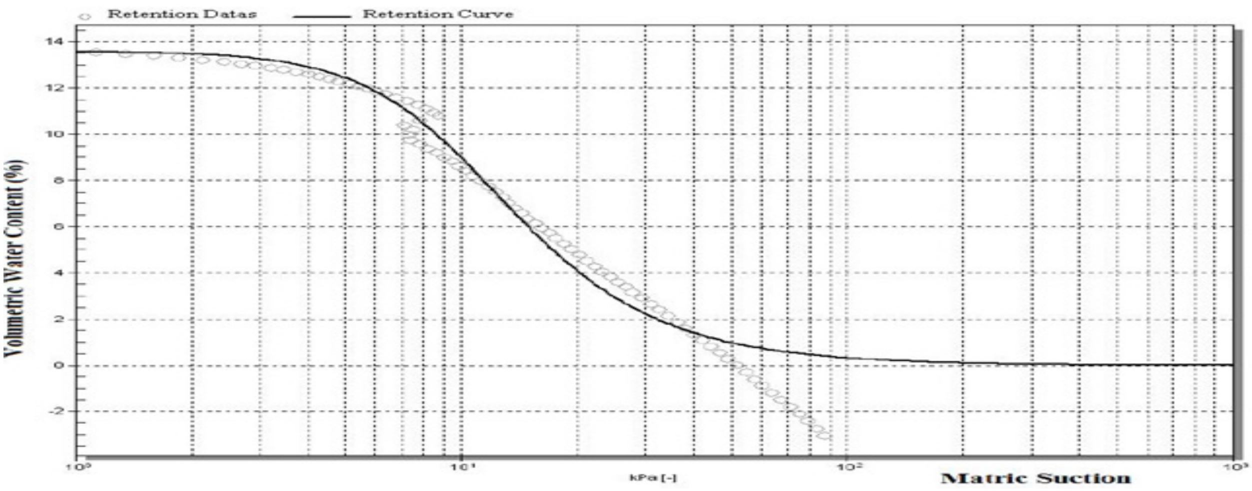


Fig. 16. Variation of Volumetric Water Content with Matric Suction for the ML soil sample (Sahin 2013).

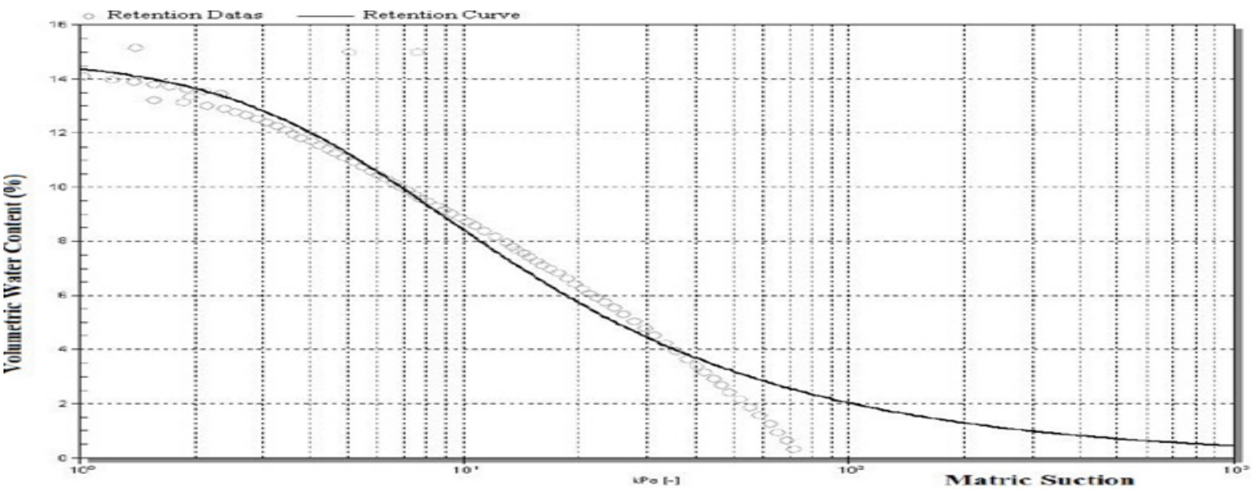


Fig. 17. Change of Volumetric Water Content with Matric Suction for the CH soil sample (Sahin 2013).

ML soil sample

CH soil sample

OL soil sample

4.2.5 Correlations with the Hyprop Test Results:

Following correlations were made using the Hyprop test results presented above.

Plasticity Index versus Time to reach the Maximum Matric Suction: Time (in days) it takes to reach the maximum matric suction (kPa) obtained in the above presented Hyprop test-result graphs were plotted against the plasticity indices (PI, %) of the 3 samples, whose properties were tabulated in Table 5. The general trend of the results was that; as PI decreases (from 20 or 30 to 5), sample becomes more granular in nature and time to reach the maximum matric suction increases,

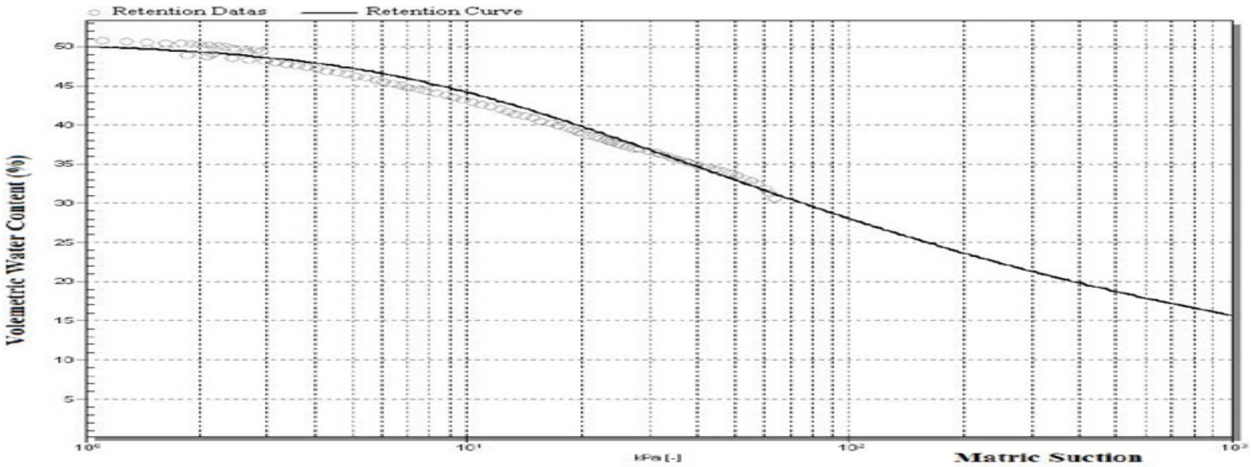


Fig. 18. Variation of Volumetric Water Content with Matric Suction for the OL soil sample (Sahin 2013).

provided that sample has lange initial void ratios. The difference between PI 20 and 30 was not so apparent and perhaps could be ignored. Low PI (ML) material has larger initial void ratio, yielding to larger pore sizes filled with larger air bubbles (compared to the other 2 samples), meaning that it takes more time to reach pressure equalization thru' the diffusion process (Egeli 1980) between air bubbles and to the point of maximum matric suction. The correlation coefficient is found as medium (0.8429), but the general trend is nearly apparent (Fig.19).

Colloid Content versus Time to reach the Maximum Matric Suction: Plotting Time (in days) it takes to reach the maximum matric suction (kPa) obtained in the Hyprop test-result graphs against the colloid contents (c, %) of the 3 samples used (second column from the last in Table 3), show that, while the colloid content decreases, (from 12 or 15 to 0.1), time to reach the maximum matric suction increases. The difference between 12 and 15 was not so apparent and perhaps could be ignored. Compared to the other 2 samples, low colloid content (ML) material had larger initial void ratio, meaning larger pores are filled with larger air bubbles. It takes more

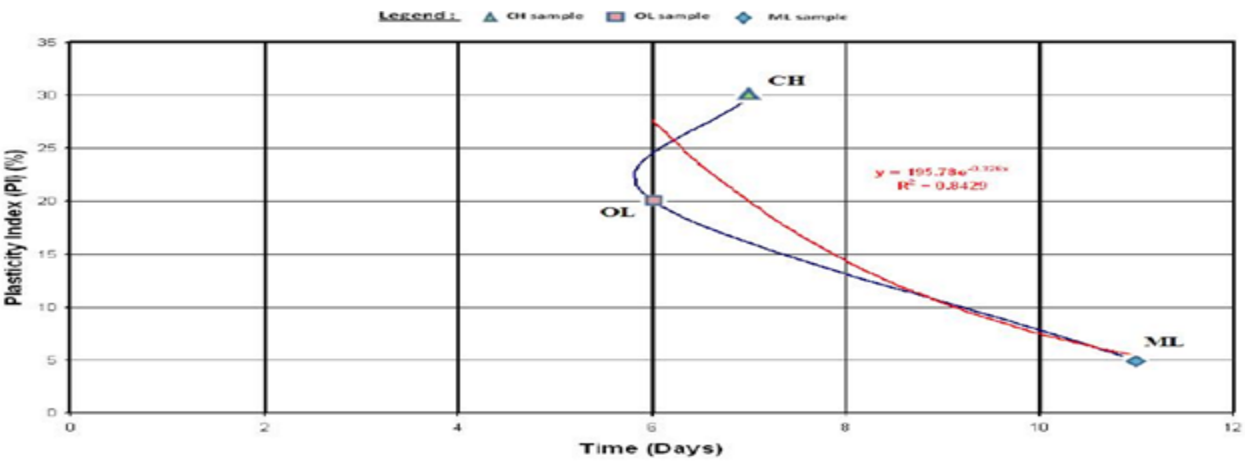


Fig. 19. Variation of Plasticity Index against Time to reach the Maximum Matric Suction (Sahin 2013).

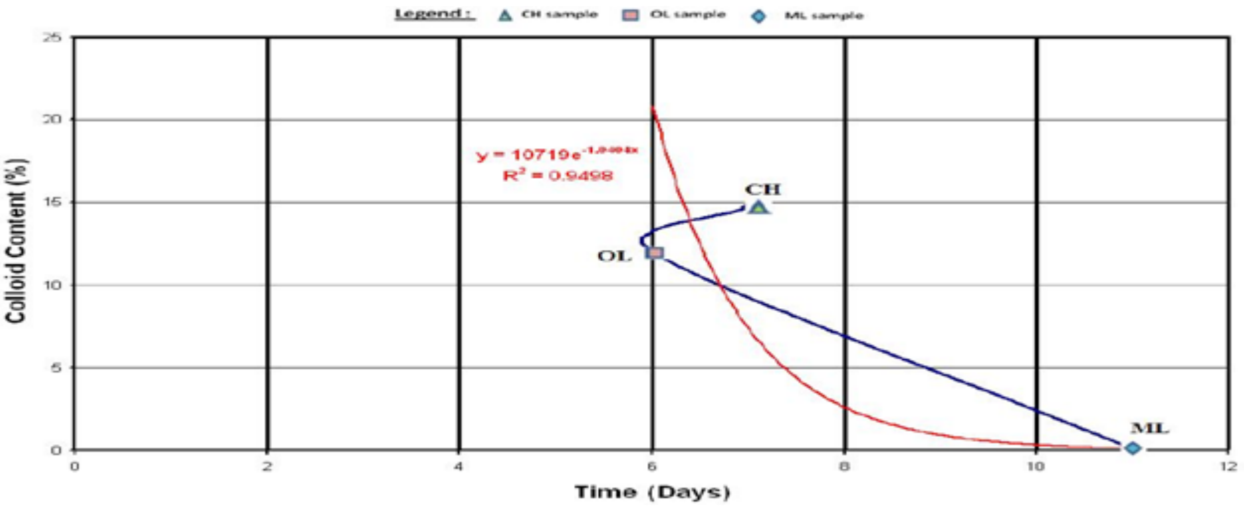


***Fig. 20.** Variation of Colloid Content against Time to reach the Maximum Matric Suction (Sahin 2013).*

time to reach pressure equalization between air bubbles thru' the diffusion process (Egeli 1992), and reaching to the point of maximum matric suction. The correlation coefficient obtain is high (0.9498), but the general trend is nearly apparent (Fig.20).

Plasticity Index versus the Maximum Matric Suction: The values of the maximum matric suction (kPa) obtained in the above presented Hyprop test-result graphs were plotted against the plasticity indices (PI, %) of the 3 samples used, whose properties were tabulated in Table 3. Results show that as PI increases, the maximum matric suction also increases. Though the correlation coefficient obtain is medium (0.7699), the general trend is clearly (Fig. 21).

Colloid Content versus the Maximum Matric Suction: Again plotting the values of the maximum matric suction (kPa) obtained in the Hyprop test-results against the colloid contents (c, %) of the 3 samples used (second column from the last in Table 3). Show that, as the colloid content increases, the maximum matric suction also increases. Though the correlation coefficient obtain is low, the general trend is understandable (Fig. 22).

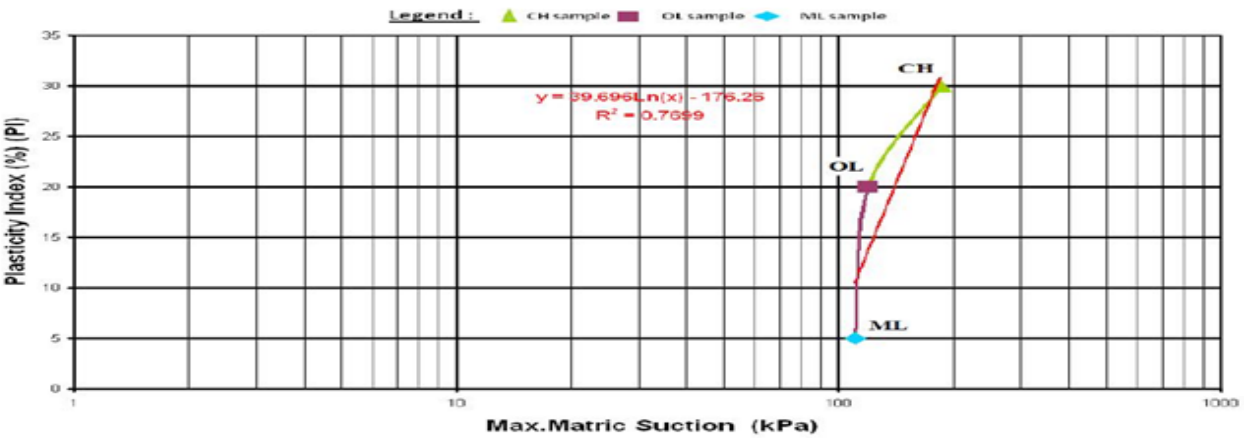


***Fig. 21.** Variation of Plasticity Index against the Maximum Matric Suction (Sahin 2013).*

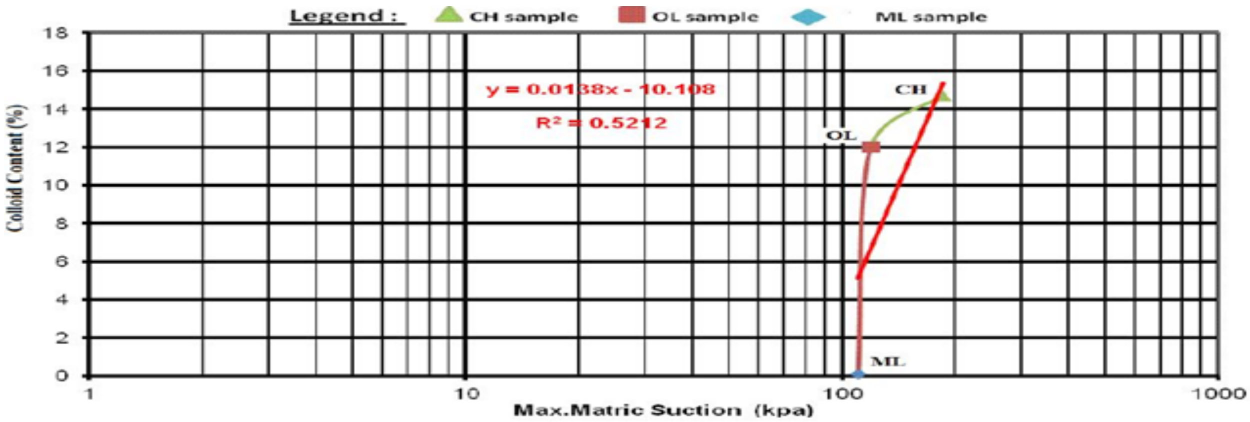


Fig. 22. Variation of Colloid Content against the Maximum Matric Suction (Sahin 2013).

Hydraulic Conductivity versus the Maximum Matric Suction: As noted earlier, Hydraulic conductivity values listed in the last column of Table 3 are the values (in mm/day) corresponding to the Maximum Matric Suction (MMS) (in kPa), obtained in the Hyprop tests conducted on the 3 samples. Unfortunately no clear trend existed. This needs further study (Fig. 23).

Hydraulic Conductivity at the Max. Matric Suction against the Plasticity Index (PI): Values of the hydraulic conductivity corresponding to the Maximum Matric Suction, MMS (in kPa) obtained in the Hyprop test-result were plotted against the Plasticity Indices (PI) of the 3 samples used in Table 3. Results show that; as PI increases, hydraulic conductivity at the max. matric suction points decreases. This is a clear trend with a high correlation coeficient (R^2=0.9981) (Fig. 24).

Hydraulic Conductivity at the Max.Matric Suction against the Colloid Content: Values of the hydraulic conductivity at the Maximum Matric Suction, MMS (in kPa) obtained in the Hyprop test-result were plotted against the colloid contents (c) of the 3 samples used in (Table 3). Results show that as colloid content increases, hydraulic conductivity at the maximum matric suction points decreases. This is a clear trend with a high correlation

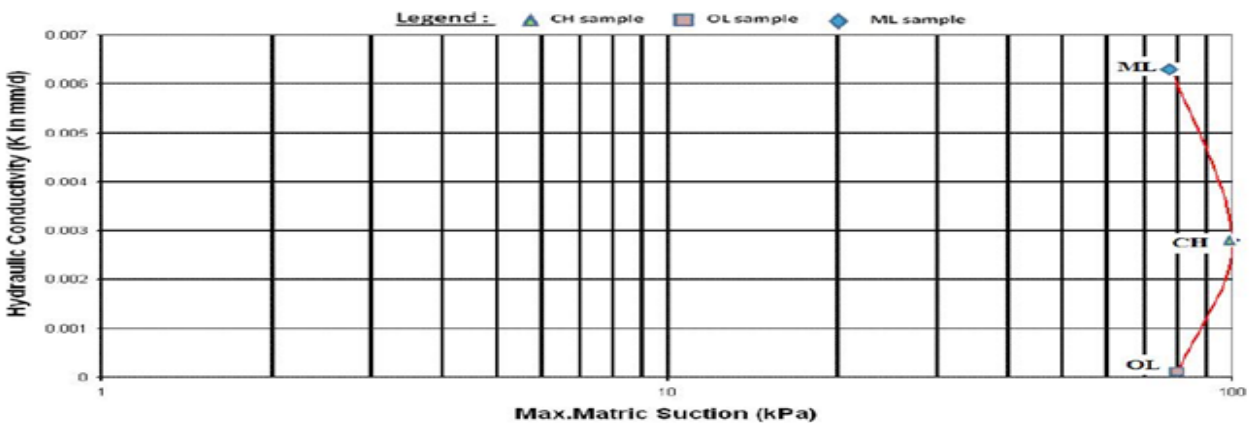


Fig. 23. Variation of Hydraulic Conductivity at the MMS against the MMS (Sahin 2013).

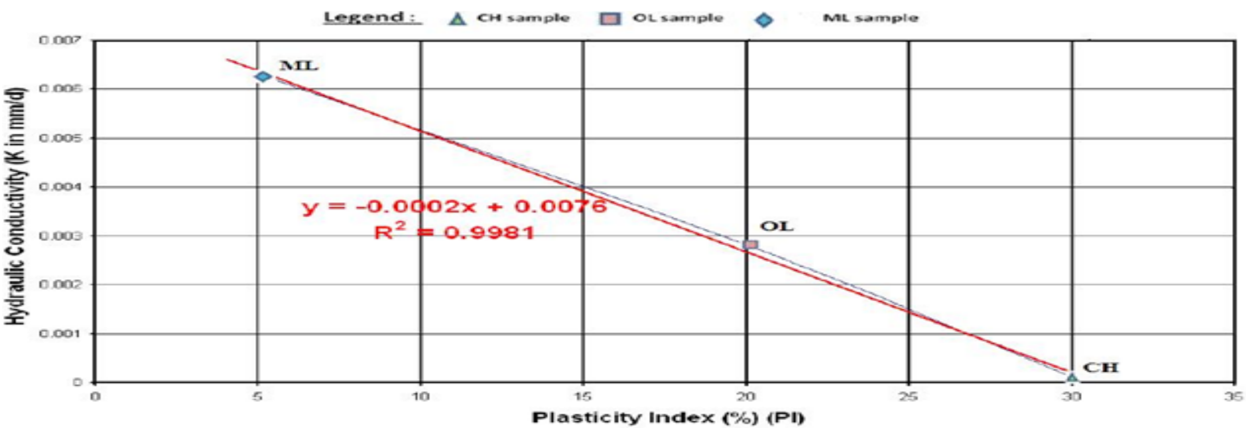


Fig. 24. *Variation of Hydraulic Conductivity at the MMS against the Plasticity Index (Sahin 2013).*

coefficient (R^2=0.9262) (Fig. 25).

5. CONCLUSIONS

A practically usable and more defining particle-size modification (USCSM) was made to the fine grained part the Unified Soil Classification System (USCS), which doesn't make any distinction in size for the fine grained soils between the silt, clay and colloid sizes. With this modification fine grained soils could be better defined and classified for their use in engineering practice, rather than using the existing USCS's more broad ranged classification process, which relies heavily on the Plasticity Chart. Also, 3 such fine grained unsaturated soils (of ML, CH and OL types) were tested with the Hyprop equipment to determine their 'water-retention and hydraulic conductivity' properties. Results yielded following conclusions:

- At no overall stress change applied to a soil sample (ie. under atmospheric pressure), matric suction within unsaturated soil pores do not stay constant, but increases with time upto a maximum point, called the maximum matric suction (MMS) and then air entry into the probes may occur, which may cause matric suction to decrease. But readings upto the first tensiometer's MMS are reliable, represent soil behaviour and can be correlated with

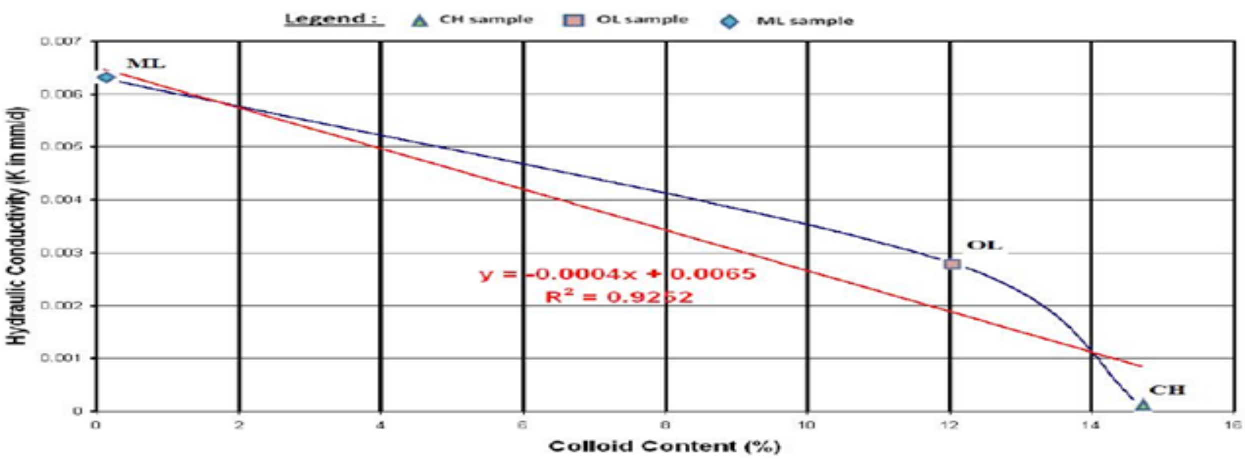


Fig. 25. *Variation of Hydraulic Conductivity at the MMS against the Colloid Content (Sahin 2013).*

other soil properties. Yet decrasing matric suction readings after the first tensiometer's MMS may mean air entry into the sample, porous tip, the measurement system etc. and schould be disregarded.

- Decreasing PI and colloid content (ie. sample becoming more granular in natüre) with higher void ratio, increases pore and air bubble size and time to reach the maximum matric suction. The reason for difference between 2 high PI with high colloid content samples and the low PI with low colloid content (ML) sample was clear with the between medium-high correlation coefficients (0.8429<R2<0.9498).
- Increasing PI, also increases the maximum matric suction (MMS). Though the correlation coefficient is not very high (0.7699), the general trend is still clear.
- Increasing colloid contents (c), also increases maximum matric suctions (MMS). Although for the obtained low correlation coefficient (0.5242),
- Hydraulic conductivity values corresponding to the maximum matric suctions (HC-MMS) were still obtained from the Hyprop test-result graphs. HC-MMS plotted against the MMS showed no clear trend for any correlation to exist. This needed further study.
- HC-MMS plotted against the PI and colloid contents (c) showed quite clear trends ($0.9262<R^2<0.9981$), as HC-MMS decreased witth increasing PI or c.

ACKNOWLEDGEMENTS:

This original research work was conducted as part of the MSc Thesis study, during which era most laboratory work has been carried out at the Geotechnics Laboratory of the Civil Engineering Department at the Izmir Institute of Technology (www.iyte.edu.tr) in Urla-Izmir, Turkey. The authors would like to expresses their gratitude to Gazi University(www.gazi.edu.tr)-Technical Education Faculty, Construction Dept.'s academic staff, in particular to Assoc.Prof. Dr. Mehmet Özer for the help received in conducting the Laser Diffraction Tests, and to Co.s: Ege-Zemin Laboratory and Ege-Zemin İns. Ltd. for providing the 3 undisturbed clay soil samples and to Izmir Institute of Technology's İYTEBAP022 project, under which financial support was provided to purchase the automatic HYPROP equipment by www.decagon.com with which unsaturated soils' laboratory tests were performed.

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