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Laboratory Measurement of Soil Suction

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Introduction

Studies have been carried out on partially saturated soils, over several years, with increasing attention. One of the major problems associated with the testing of unsaturated soil is measuring the negative pore pressure (suction) exhibited by it (Lee and Wray, 1995; Sreedeep, 2002). The role of soil suction in geotechnical engineering and its practice is very well recognized and many models have been developed (Brooks and Corey, 1964; Mcqueen and Miller, 1968; van Genuchten, 1980; Fredlund and Xing, 1994; Fredlund et al., 1997 and 1998; Singh et al., 2002). Suction measurement finds application in transportation engineering projects (Gourley and Schreiner, 1995; Oberg, 1995), environmentally sensitive projects viz. waste containment in landfill sites (Sudhakar and Revanasiddappa, 2000) and nuclear storage installations where the soil permeability is a function of suction (Rahardjo et al., 1995; Blatz and Graham, 2000; Singh et al., 2001). Hence, several efforts have been made by researchers to measure suction of the remoulded soil samples (Lee and Wray, 1995; Woodburn and Lucas, 1995; Truong and Holden, 1995). However, most of these studies utilize devices that are quite elaborate and expensive. With this in view, several researchers have demonstrated the utility of tensiometers for measuring soil suction easily and quite efficiently (Stannard, 1992; Samjstrla and Harrison, 1998; Kuriyan, 2001; Sreedeep, 2002; Singh et al., 2002).

Efforts have been made by researchers to demonstrate influence of volume-mass properties of the soil mass on its suction (Fredlund et al., 1997). Hence, measurement of volumetric water content of the soil mass

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becomes a necessity. In this context, the utility of Time Domain Reflectometry in measuring volumetric water content of the soil has been demonstrated by several researchers (Topp et al., 1980; Roth et al., 1990; Dalton, 1992). Knowing the volumetric water content of the soil and its suction, the soil-water characteristic curve, which is a graphical plot between water content (volumetric or gravimetric) and soil suction can be developed easily (Fredlund et al., 1997).

With this in view, the reliability and efficiency of a P3S type TDR probe in measuring volumetric water content of locally available soil, denoted as Soil S, and commercially available white clay, denoted as Soil C, and the utility of an insertion tensiometer for measuring low soil suction (< 90 kPa) has been demonstrated in this technical note.

Experimental Investigations

Measurement of Volumetric Water Content

The P3S type TDR probe, shown in Fig.1, with a readout device TRIME-FM, developed and supplied by IMKO Micromoduletechnik, GmbH, has been used in the present study. The TRIME-FM directly displays the volumetric water content of the soil sample. Two soils, with their properties listed in Table 1 have been chosen for the present study. For conducting the basic calibration of the TDR probe, a calibration connector supplied by the manufacturer is attached to it and the probe is inserted into a container

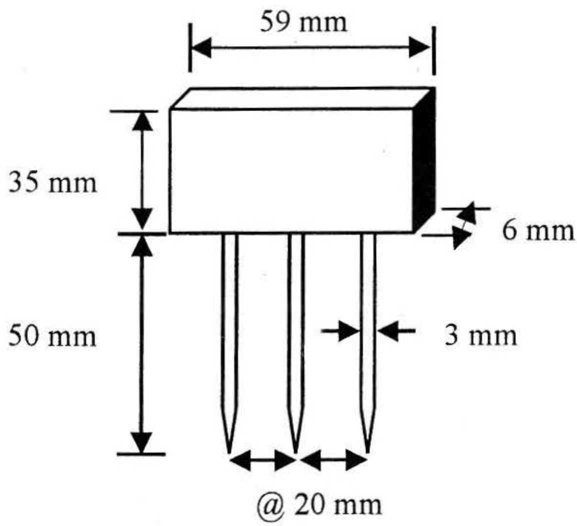

FIGURE 1 : Details of the P3S Type TDR Probe

TABLE 1 : Physical Properties of the Soils Considered for the Present Study

Soil Property	Soil S	Soil C
Specific gravity	2.62	2.65
Particle size characteristics:		
Sand:	56	0
Coarse (4.75 - 2.0 mm) (%)	2	-
Medium (2.0 - 0.420 mm) (%)	23	-
Fine (0.420 - 0.074 mm) (%)	31	-
Fines:		
Silt size (0.074 - 0.002 mm) (%)	33	39
clay size (< 0.002 mm) (%)	11	61
Consistency limits:		
Liquid limit (%)	44	46
Plastic limit (%)	34	25
Plasticity index (%)	10	21
Soil Classification (USCS)	ML	CL
Standard Proctor Compaction		
γ_{dmax} (kN/m^3)	15.9	13.9
OMC (%)	21.4	20.8

containing dry glass beads. This yields the reference volumetric water content of 2.8%. The procedure is repeated with the probe inserted in saturated glass beads and it is ensured that the displayed reference volumetric water content is 43.8% (Sreedeep, 2002).

An adequate amount of oven-dried soil was mixed with different water contents, and stored for 24 h in airtight bags, for its preconditioning and maturing. The soil sample was prepared in a Perspex cylindrical mould of 115 mm diameter by compacting the soil in three layers, by tamping it with the help of a flat bottom hand rammer to achieve the required dry unit weight, γ_d, (= 12.0, 13.0 and 14.0 kN/m^3). After preparing the soil sample, the dummy rod supplied by the manufacturer was used to create three holes in the soil mass. Later, the TDR probe was inserted into these holes and the volumetric water content of these soil samples, θ_m, was recorded. After these observations were recorded, the probe was taken out of the soil mass and a small amount of the soil, from three different locations of the soil sample, was used to obtain the average gravimetric water content, w. Using Eqn.1, the volumetric water content, θ_c, of the soil sample has been computed.

TABLE 2 : Details of Jib-P Insertion Type Tensiometer

Tensiometer tube	
Material	Glass
Length (mm)	130
Height of the viewing window (mm)	44
Diameter (mm)	16.5
Cone:	
Material	Ceramic
Diameter (mm)	6.5
Length of the cone (mm)	30
Insertion depth (mm)	35
Suction measurement range of ceramic thimble (AEV)	0 - 90 kPa

$$\theta_c = w \times \left(\frac{\gamma_d}{\gamma_w} \right) \tag{1}$$

where γ_d is the dry unit weight of the soil and γ_w is the unit weight of water.

Measurement of the Soil Suction

The suction of the soil sample was measured with the help of a Jib-P insertion tensiometer manufactured by TENSIO-TECHNIK, Geisenheim, Germany, and with its details listed in Table 2. As shown in Fig.2, the test

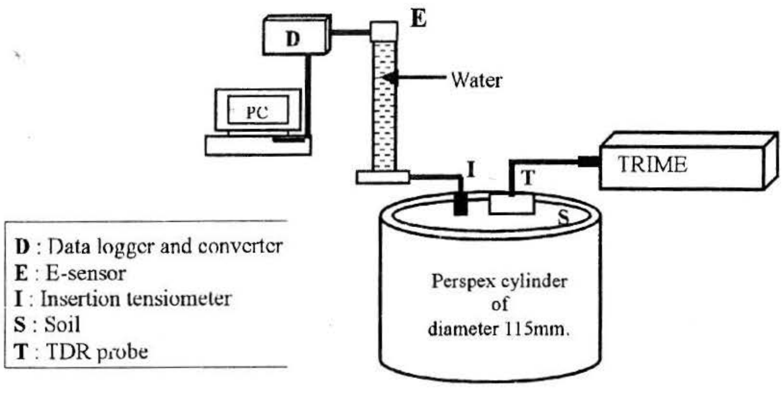

FIGURE 2 : Details of the Test Setup for Suction Measurement

setup includes a Perspex cylinder in which soil sample is prepared, a TDR probe, and a insertion tensiometer with E-sensor, which is used to measure suction continuously with time. The output of E-sensor (in mA) is recorded using a data logger and a PC. The output of the E-Sensor ranges from 3.96 mA to 20 mA, for which the corresponding suction pressure would be 0 and 90 kPa, respectively, as mentioned by the manufacturer (TENSIO-TECHNIK, Geisenheim, Germany). Using these values, a relationship (Eqn.2) for obtaining the soil suction from E-sensor output was developed (Sreedeep, 2002).

$$\text{Suction (kPa)} = \left[-22.22 + 5.61 \times \text{measured current (mA)}\right] \tag{2}$$

The soil sample was compacted corresponding to different dry unit weight, γ_d, (= 10.0, 11, 12, 13, 14 and 14.5 kN/m^3) in a Perspex mould of 115 mm diameter and 70 mm height. To ensure proper contact of the tensiometer with the soil mass, a coring tube (diameter 6 mm), which is slightly less in the diameter than that of the ceramic thimble of the tensiometer, has been used to create a hole which is long enough to accommodate the tensiometer thimble.

Prior to the start of the test, the tensiometer tube was filled with demineralised and deaerated water and its ceramic thimble soaked in water for almost 24 h. This ensures that there is no entrapped air in the ceramic thimble and the possibility of cavitation to occur gets minimized. The insertion tensiometer was placed in the soil sample and the tensiometer readings were recorded over a period of time. These tests were conducted in a controlled humidity and temperature chamber so as to reduce the influence of environmental effects. The top of the soil sample was sealed using an aluminum foil to minimize loss of moisture (Sreedeep, 2002).

Results and Discussion

Volumetric water content of various soil samples measured with the help of the TDR probe, θ_m, is plotted against the volumetric water content computed using Eqn.1, θ_c, as depicted in Fig.3. It can be noticed from the obtained data that the computed and measured volumetric water contents match well for $\theta_m \leq 40\%$. Though $\theta_m > \theta_c$, a reasonably good agreement between the two volumetric water contents is noticed for $\theta_m \geq 40\%$. This can be attributed to the fact that for higher gravimetric water contents, w, the compaction of the soil sample becomes very difficult and packing of soil to a required dry unit weight becomes less pronounced. However, it is interesting to note that for the data presented in the figure, the regression coefficient is close to unity and the slope of θ_c vs. θ_m relationship is 0.8727. Similar trend follows for the white clay also. However, for the sake of

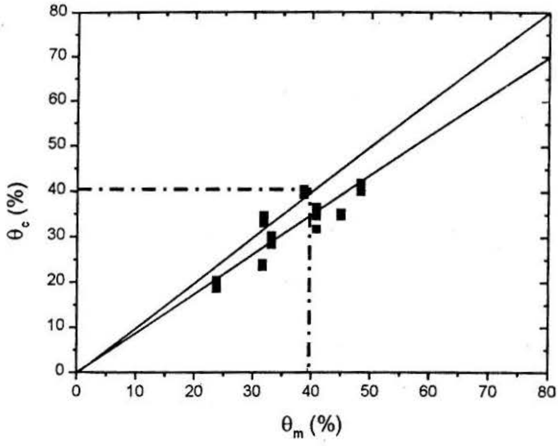

FIGURE 3 : θ_c versus θ_m Relationship for the Locally Available Soil (γ_d = 13 kN/m^3)

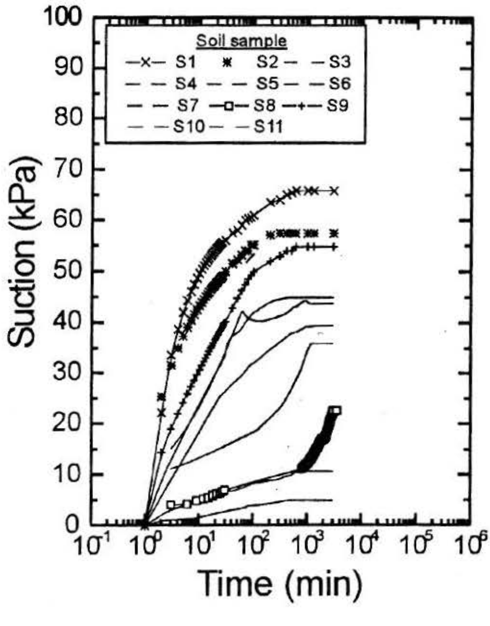

FIGURE 4 : Variation of the Soil Suction with Time for the Locally Available Soil Samples

brevity, the results are not being presented here in. This exhibits reliability of the TDR probe for measuring volumetric water content of the soil mass.

Suction Measurements

Soil suction was measured for the locally available soil (Soil S) and white clay (Soil C), at various compaction states as listed in Table 3. Using Eqn.2, the datalogged values (in mA) are converted into suction (in kPa). From these values, suction versus time response has been plotted, for Soil S, as depicted in Fig.4. For the sake of brevity, the plot for Soil C is not presented. From Fig.4, the final suction values, have been determined and are presented in Table 3.

TABLE 3 : Details of the Soil Samples

Soil	Sample	γ_d (kN/m^3)	w (%)	S_r (%)	e	Suction (kPa)
S	S1	13.0	11.2	27.35	1.02	62
	S2	12.1	13.7	28.78	1.18	57
	S3	12.1	15.8	33.26	1.18	54
	S4	12.0	20.9	44.1	1.18	43
	S5	12.2	24.8	52.25	1.18	36
	S6	12.1	33.1	69.6	1.18	5
	S7	12.1	30.8	65.11	1.18	8
	S8	12.0	32.8	69.0	1.18	22.5
	S9	10.0	18.3	28.57	1.62	54
	S10	10.1	25.7	40.00	1.62	42
	S11	10.0	29.5	46.00	1.62	40
	S12	11.2	28.8	54.62	1.38	64
	S13	12.1	25.8	57.19	1.18	58
	S14	13.1	26.6	68.25	1.02	61
	S15	13.2	27.1	75.51	0.94	60
	S16	14.2	26.8	80.76	0.87	55
	S17	14 5	27.5	89.05	0.81	59
C	C1	10.1	28.0	45.85	1.62	67
	C2	11.2	27.5	52.12	1.38	71
	C3	12.1	27.6	60.45	1.21	71
	C4	13.2	27.8	70.89	1.04	66
	C5	14.1	27.4	81.6	0.89	69
	C6	12.2	32.2	70.53	1.208	63
	C7	12.1	36.7	80.42	1.208	61
	C8	12.1	29.7	65.15	1.208	66

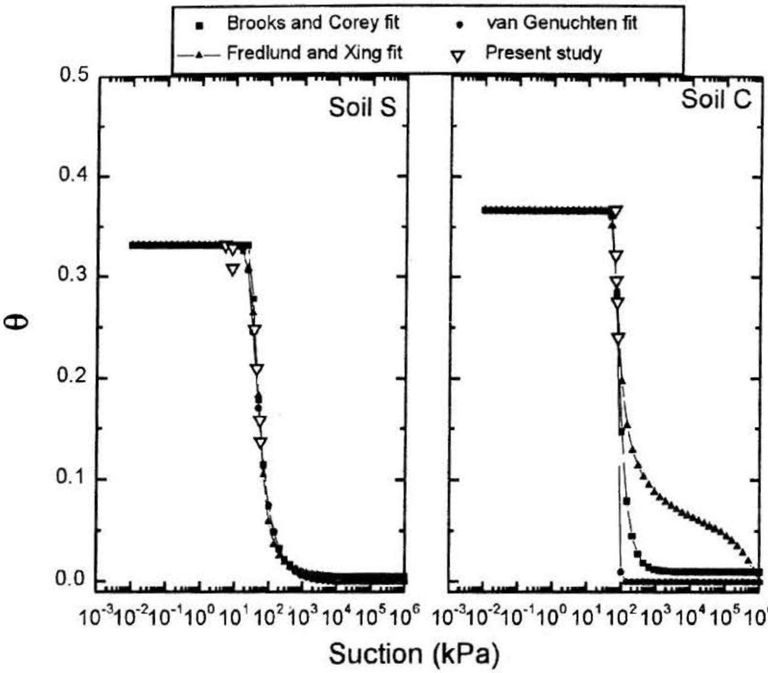

FIGURE 5 : SWCCs Obtained for the Two Soils

Development of SWCC from the Obtained Data

The suction values presented in Table 3, have been used for developing SWCC with the help of Eqns.3, 4 and 5, proposed by Fredlund and Xing (1994), van Genuchten (1980) and Brooks and Corey (1964), respectively, and presented in Fig.5.

$$w(\psi) = w_s \times \left[1 - \frac{\ln\left(1+\frac{\psi}{h_r}\right)}{\ln\left(1+\frac{10^6}{h_r}\right)}\right] \times \left[\left[\ln\left\{\exp(1) + \left(\frac{\psi}{a_f}\right)^{n_f}\right\}\right]^{m_f}\right]^{-1} \quad (3)$$

$$w(\psi) = w_r + \left(w_s - w_r\right)^{*}\left[\left[1+\left(a_{vg}\psi\right)^{n_{vg}}\right]^{m_{vg}}\right]^{-1} \quad (4)$$

$$w(\psi) = w_r + \left(w_s - w_r\right)^{*}\left[\frac{a_c}{\psi}\right]^{n_c} \quad (5)$$

TABLE 4 : Values of the Parameters Used in Fitting Functions

Fitting function	Parameter	Soil S	Soil C
Brooks and Corey (1964)	a_c (kPa)	30.99	64.79
	n_c	0.19	1.75
	R^2	0.9672	0.9972
	RWC (%)	0.6	0.1
	AEV (kPa)	30.90	62.96
van Genuchten (1980)	a_{vg} (kPa^{-1})	0.015	0.0099
	n_{vg}	4.68	12.51
	m_{vg}	0.23	11.55
	R^2	0.9809	0.9877
	RWC (%)	0.1	0.0
	AEV (kPa)	52.13	66.40
Fredlund and Xing (1994)	a_f (kPa)	76.23	73.78
	n_f	1.29	13.89
	m_f	0.67	0.78
	h_r (kPa)	699005.8	165613.8
	R^2	0.9941	0.9999
	RWC (%)	29.5	29.9
	AEV (kPa)	31.35	65.03

where $w(\psi)$ = gravimetric water content at any suction, ψ,

w_r = residual water content, RWC,

w_s = gravimetric water content at saturation,

a_f and a_{vg} = soil parameters primarily dependent on the air entry value, AEV,

n_f and n_{vg} = soil parameters that depend on the rate of extraction of water from the soil beyond the AEV,

m_f = soil parameter which is a function of the RWC,

h_r = suction (in kPa) corresponding to the RWC,

m_{vg} = fitting parameter,

a_c = bubbling pressure (in kPa), and

n_c = pore size index.

The parameters involved in Eqns.3 to 5, corresponding to the soils used in this study are presented in Table 4. It can be noted that the regression coefficient, obtained for various fitting functions are close to unity. This indicates the usefulness of an insertion tensiometer for establishing the soil-water characteristic curve (SWCC) for the locally available soil and the white clay. The SWCC can be used for estimating properties like hydraulic conductivity (Singh et al., 2002), shear strength (Rahardjo et al., 1995) and compressibility (Sudhakar and Revanasiddappa, 2000), etc., for unsaturated soils.

Conclusions

In the present study, an effort was made to measure soil suction with the help of insertion tensiometer. The volumetric water content of the soil has been measured with the help of a TDR probe and its calibration has been done. Based on the study, following conclusions can be drawn.

1. TDR probe yields reliable results. The measured volumetric water content matches very well with the computed one for the soil mass. However, a very small deviation is observed for the soil samples compacted at higher water contents.

2. Utility of an insertion tensiometer for developing the SWCC for a locally available soil and white clay is established.

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Notations

θ	=	volumetric water content at any suction ψ;
θ_c, θ_m	=	computed and measured volumetric water content;
γ_d	=	dry unit weight;
γ_{dmax}	=	maximum dry unit weight;
AEV	=	air entry value;
a_f, a_{vg}	=	soil parameter which is a function of air entry value;
a_c	=	the bubbling pressure (in kPa)
h_r	=	suction corresponding to RWC;
m_f	=	soil parameter which is a function of RWC;
m_{vg}	=	a fitting parameter;
n_c	=	pore size index.
n	=	total pore size classes;
n_f, n_{vg}	=	soil parameter which is a function of rate of extraction of water from the soil beyond the AEV;
OMC	=	optimum water content;
RWC, w_r	=	the residual water content;
S_r	=	degree of saturation;
w	=	gravimetric water content;
$w(\psi)$	=	gravimetric water content at any suction, ψ;
w_s	=	saturation water content.