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Laboratory investigations on extremely high suction measurements for fine-grained soils

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Abstract. A Dewpoint PotentiaMeter (WP4) was used to measure suction of two fine-grained soils: a locally available silty soil and commercially available white clay, rapidly. Using these results, efforts were made to check the suitability and efficiency of various fitting functions, for defining the soil–water characteristic curve, SWCC, for high suction ranges (0–80 MPa). In addition to this, a knowledge-based database SoilVision 3.34 was used to estimate the SWCC using Pedo-transfer functions, PTFs. The study brings out that the Fredlund et al. [1997, *Proceedings of the 3rd Symposium on Unsaturated Soil*, Rio de Janeiro, Brazil, pp. 13–23] PTF yields the best estimate of SWCC for fine-grained soils. The influence of the soil type and dry unit weight, on suction and the SWCC fitting parameters, have also been studied.

Key words. Dewpoint PotentiaMeter, fine-grained soils, pedo-transfer function, soil suction, soil–water characteristic curve.

Notations. a_c: bubbling pressure in kPa; AEV: air entry value; a_f, a_{vg}: soil parameters which are dependent on the AEV; h_r: suction corresponding to w_r; M: molarity of the KCl solution; m_f: soil parameter which is a function of w_r; m_{vg}: fitting parameter; n_c: pore size index; n_f, n_{vg},: parameters which depend on the rate of extraction of water from the soil beyond AEV; p: vapour pressure of air; p_0: saturation vapour pressure; PTF: pedo-transfer function; R: universal gas constant; S_r: degree of saturation; T: temperature of the sample in K; w: gravimetric water content; $w(\psi)$: gravimetric water content at any suction, ψ; w_0: optimum water content; w_r: residual water content; w_s: gravimetric water content at saturation; χ: molecular mass of water; γ_d: dry unit weight; γ_{dmax}: maximum dry unit weight; ψ: total suction; ψ_m: matric suction; ψ_o: osmotic suction.

1. Introduction

The role of soil suction in the practice of geotechnical engineering is well recognised and models that incorporate the effect of suction on soil properties have been developed (Garbulewski and Zakowicz, 1995; Delage et al., 1998; Sudhakar and Revanasiddappa, 2000; Sillers and Fredlund, 2001). These studies indicate that soil

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suction, ψ, is mandatory to understand the behaviour of unsaturated soil to a great extent.

Studies have been conducted by several researchers to develop the soil–water characteristic curve, SWCC, which is the relationship between soil suction, ψ, and the water content, w. Further, the utility of the SWCC for determining unsaturated soil properties such as hydraulic conductivity, shear strength, compressibility and swelling potential has also been demonstrated by several researchers (McKeen, 1992; Garbulewski and Zakowicz, 1995; Huang et al., 1995; Rahardjo et al., 1995; Vanapalli et al., 1996; Delage et al., 1998; Singh et al., 2001; Singh and Sneha, 2002; Sreedeep and Singh, 2004a).

Several soil suction measurement devices have been used for establishing the SWCC. Tensiometer, measures the suction directly (Stannard, 1992; Sreedeep and Singh, 2004b), whereas instruments such as pressure-plate apparatus, transistor psychrometer, thermal conductivity suction sensor and a centrifuge enable estimation of soil suction, indirectly (Lee and Wray, 1995; Truong and Holden, 1995; Singh et al., 2001; Singh and Sneha, 2002). The results have been used to develop SWCC by employing various fitting functions proposed by the researchers (Brooks and Corey, 1964; van Genuchten, 1980; Fredlund and Xing, 1994). However, in most of these studies it is observed that the data for low ranges of suction have been used for fitting the SWCC. Hence, the accuracy and validity of these fitting functions for higher ranges of the soil suction must be investigated.

In addition, several Pedo-transfer functions (PTFs) that can be used for estimating the SWCC from the grain-size distribution and volume mass properties of the soil have been developed by researchers (Arya and Paris, 1981; Rawls and Brackensiek, 1985; Tyler and Wheatcraft, 1989; Scheinost et al., 1996; Fredlund et al., 1997). However, validity and efficiency of these PTFs for different fine-grained soils have not been investigated in details vis-à-vis the results obtained from laboratory experiments, in particular, in the higher range of soil suction.

With this in view, a Dewpoint PotentiaMeter (WP4), which works based on the 'chilled mirror concept' (ASTM D 6836-02, 2003; Leong et al., 2003), and which can measure up to 80 MPa suction, was used in this study. It must also be noted that WP4 measures total suction, ψ, which is equal to the sum of the matric suction, ψ_m, and the osmotic suction, ψ_0 (McKeen, 1992). However, not many studies are reported in the literature, which used WP4 for measuring soil suction.

Two fine-grained soils: a locally available silty soil and commercial white clay were selected for this study and the results were used to develop SWCC for these soils using the knowledge-based database, SoilVision 3.34 (SoilVision, 2003). This database is also useful for estimating saturated and unsaturated soil properties, based on the volume–mass properties and grain-size distribution.

Using the experimental results, the efficiency of various fitting functions in developing SWCC, for high range of the suction, and to evaluate various PTFs was checked. This study also assists in understanding the influence of soil type and dry unit weight on the SWCC and various parameters used in the fitting functions.

2. Details of the Dewpoint PotentiaMeter (WP4)

A Dewpoint PotentiaMeter (WP4) was used in the present study (ASTM 6836-02, 2003; Leong et al., 2003). The device consists of a sealed block chamber equipped with a mirror, dew point sensor, which is a photoelectric cell, a temperature sensor, which acts as a thermocouple, an infrared thermometer (optical sensor) and a fan. A soil specimen of approximately 6 cc is placed in the PVC cup and equilibrated with the air in the headspace of the sealed block chamber for its relative humidity. At equilibrium, the water potential of air in the chamber is the same as the water potential or suction of the sample, which occurs within 5–15 min. A chamber fan is provided to accelerate the process of equilibration.

The relationship between the total suction, ψ, and the vapour pressure of air in the headspace can be expressed using Kelvin's equation (ASTM D 6836-02, 2003):

$$\psi = \frac{RT}{\chi} \ln \frac{p}{p_0}, \tag{1}$$

where R is the universal gas constant, T is the temperature of the sample in K, χ is the molecular mass of water (= 18), p is the vapour pressure of air, and p_0 is the saturation vapour pressure.

A photoelectric cell detects the condensation on the mirror and the thermocouple records the temperature at which condensation occurs. The infrared thermometer is used to measure the specimen temperature. At equilibrium, the headspace vapour pressure is measured and the saturation vapour pressure is computed. With the assistance of the in-built software, the total suction of the soil specimen (in MPa and pF units) is displayed on the LCD panel of the WP4 along with its temperature.

Before using the WP4, it was calibrated by adopting the following procedure and using standard solution of 0.5 M KCl, which should yield a suction of 2.19 ± 0.1 MPa, at 25 °C, (Decagon Services Ltd., 2002). In order to generalise the efficiency of the WP4, standard KCl solutions of different molarity, M, were used and a relationship between ψ_0 and M was established, as depicted in Figure 1. These results were compared with the values prescribed by the manufacturer. It was noted that the slope of the experimental results (i.e., equal to 4.79) is 1.10 times higher than the slope of the standard results (i.e., equal to 4.37). As such, the measured suction values should be reduced by a factor 1.1 to obtain the correct total soil suction. It should be noted that in the absence of salts and other contamination in the soil mass, ψ_0 can be neglected and the device will yield a total suction, ψ, equal to the matric suction, ψ_m.

3. Details of the Database SoilVision 3.34

SoilVision 3.34 (2003) is a knowledge-based system database, which can be used for developing the SWCC by using different fitting functions and the measured suction data. The commonly used fitting functions proposed by Fredlund and Xing (1994),

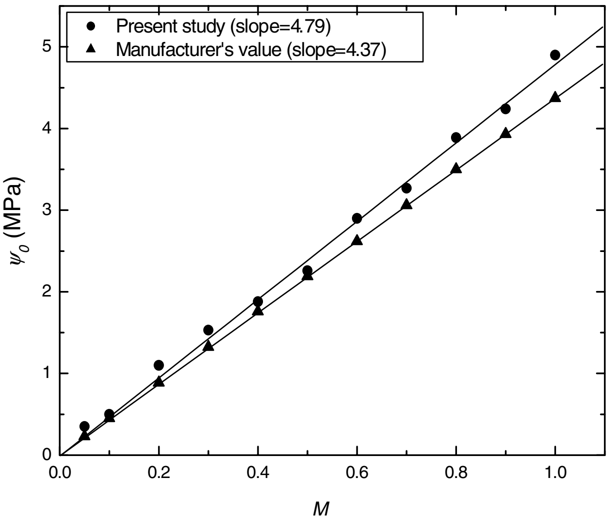

Figure 1. Calibration of the WP4 using KCl solutions of different molarity.

van Genuchten (1980) and Brooks and Corey (1964), represented by Equations 2, 3 and 4, respectively are used in this study. However, the most important feature of this database is its ability to estimate the SWCC of a soil from its grain-size distribution and volume–mass properties, without measuring the soil suction.

$$w(\psi) = w_s \left[1 - \frac{\ln\left[1 + \frac{\psi}{h_r}\right]}{\ln\left[1 + \frac{10^6}{h_r}\right]} \right] \times \left[\left[\ln\left[\exp(1) + \left(\frac{\psi}{a_f} \right)^{n_f} \right] \right]^{m_f} \right]^{-1}, \tag{2}$$

$$w(\psi) = w_r + (w_s - w_r) \times \left[\left[1 + (a_{vg}\psi)^{n_{vg}} \right]^{m_{vg}} \right]^{-1}, \tag{3}$$

$$w(\psi) = w_r + (w_s - zw_r) \times \left[\frac{a_c}{\psi} \right]^{n_c}, \tag{4}$$

where $w(\psi)$ is the gravimetric water content at any suction, ψ; w_r, is the residual water content; w_s is the gravimetric water content at saturation; a_f, and a_{vg} are soil parameters primarily dependent on the air entry value, AEV; n_f and n_{vg} are soil parameters that depend on the rate of extraction of water from the soil beyond AEV; m_f is the soil parameter and is a function of w_r; h_r is suction (in kPa) corresponding to w_r; m_{vg} is a fitting parameter; a_c is the bubbling pressure (in kPa) and n_c is the pore size index.

4. Experimental Investigations

4.1. SOIL PROPERTIES

Soils used in the present study were characterised for grain size distribution (ASTM D 422, 1994), specific gravity (ASTM D 854, 1994) and consistency limits (ASTM D

4318-93, 1994), and these properties are listed in Table 1. The standard Proctor compaction characteristics (ASTM D 698, 1994) of these soils are presented in Figure 2. It can be noted that the silty soil exhibits a maximum dry unit weight, γ_{dmax} of 16.9 kN/m^3 corresponding to an optimum water content, w_0, of 19.7%, and a degree of saturation, S_r, of 84.4%. While, for the white clay γ_{dmax} is equal to 14.1 kN/m^3 corresponding to w_0 of 21.2% and S_r of 63.7%.

4.2. SOIL SUCTION MEASUREMENTS

The air-dried soils were mixed with the required amount of demineralised water and stored for approximately three days in a humidity chamber, for maturing. To achieve a certain dry unit weight, γ_d, as listed in Table 2 and denoted as * in Figure 2, the required amount of the 'matured' soil is compacted in three layers by providing 39 blows to each layer in a stainless steel mold (37.5 mm internal diameter and 75 mm long) with the help of a miniature compactor developed by Kolay and Singh (2001). Here it must be noted that as the main focus of the study is to determine the effect of soil type and dry unit weight on its suction, suction measurements were conducted on the samples with same grain-structure (depicted as * in Figure 2). The compacted soil samples were saturated in a vacuum desiccator, which was connected to a vacuum pump, for 2–3 days. Later, these samples were taken out of the desiccator and a 60 mm thick slice was cut to determine the gravimetric water content, w, and saturation, S_r (ASTM D 2216, 1992). Three such observations were made and the average values are listed in Table 2. The data presented in the table indicates that the soil samples were fully saturated (i.e., S_r ranges from 99.2% to 99.9%). The remaining 15 mm thick slice of these samples was used to determine the SWCC as discussed below.

Table 1. Properties of the fine-grained soils used in the study

Soil property	Silty soil	White clay
Specific gravity	2.79	2.65
Particle size characteristics		
Sand (%)		
Coarse (4.75–2.0 mm)	4	–
Medium (2.0–0.425 mm)	17	–
Fine (0.425–0.075 mm)	28	–
Fines (%)		
Silt size (0.075–0.002 mm)	36	39
Clay size (< 0.002 mm)	15	61
Consistency limits (%)		
Liquid limit	41	46
Plastic limit	28	25
Plasticity index	13	21
USCS classification	ML	CL

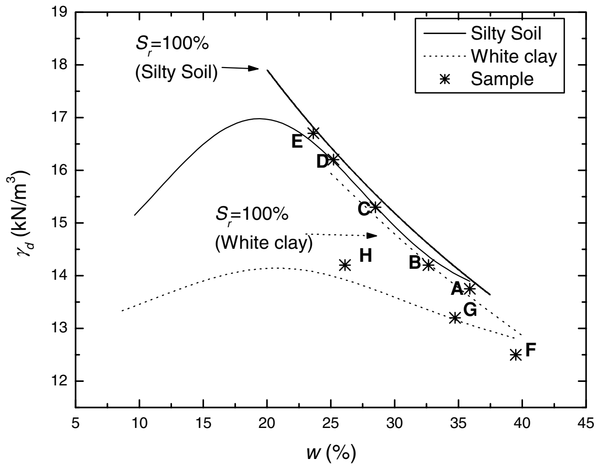

Figure 2. Standard Proctor compaction characteristics of the soils used in the study.

Table 2. Details of the soil samples used for suction measurement

Soil	Sample designation	γ_d(kN/m^3)	Molding state		After saturation state	
			w (%)	S_r (%)	w (%)	S_r (%)
Silty soil	A	13.75	35.9	97.3	36.8	99.8
	B	14.21	32.6	94.4	34.5	99.9
	C	15.31	28.5	96.7	29.4	99.7
	D	16.22	25.2	97.6	25.6	99.2
	E	16.75	23.6	98.9	23.8	99.8
White clay	F	12.50	39.5	93.5	42.2	99.8
	G	13.20	34.7	91.4	37.9	99.7
	H	14.20	26.1	79.8	32.6	99.7

As per the guidelines provided by the manufacturer, the WP4 device was placed in a temperature and humidity controlled room. It was ensured that the bottom of the PVC cup was fully covered with the soil and the cup was almost half empty, as suggested by the manufacturer (Decagon Services Ltd., 2002). With this in view, 1.5-mm thick stainless steel rings, which are 35 mm in internal diameter and 6.5 mm in height and which have a sharp edge, were fabricated. These rings were tamped into the remaining 15 mm thick portion of the samples with the help of a light wooden mallet. Later, both sides of these rings containing the soil specimen were trimmed and levelled using a spatula. The rings were placed into different PVC cups for the suction measurement. After each suction measurement the specimen was taken out of the WP4 chamber and left for air-drying for about 10–15 min. Before starting the next suction measurement, the weight of the ring along with specimen was recorded. This process was repeated several times until the total suction was found to be close to 80 MPa. At the end of the test, the ring with the soil specimen was placed in an oven to determine its dry weight. Using the dry and wet weights of the specimen, the gravimetric water content, w, was computed for each stage of suction measurements.

5. Results and Discussion

The soil suction test results are presented in Tables 3 and 4, for the silty soil and for the white clay, respectively, corresponding to different states of compaction (designated as Sample). As stated earlier, the recorded values of total suction, ψ, are corrected by dividing them by 1.1 and the results were used to develop SWCC for these soils, using the Fredlund and Xing (1994), van Genuchten (1980), and Brooks and Corey (1964) equations. For the sake of brevity, the SWCCs for only Sample A are presented in Figure 3. It can be noted that the Brooks and Corey and Fredlund and Xing fitting functions are valid for high ranges of the suction for fine-grained soils. However, van Genuchten fitting function exhibits improper trend in the higher ranges of ψ (> 20 MPa).

Details of various parameters used for fitting SWCCs for the silty soil and the white clay are presented in Tables 5 and 6, respectively. It can be noted from the data presented in these tables that the Fredlund and Xing fit (Equation 2), van Genuchten fit (Equation 3) and Brooks and Corey fit (Equation 4) yield values of air entry value, AEV, and residual water content, w_r, which are similar for different samples. However, the values of AEV and w_r, for the same sample, obtained from different fitting functions are found to be somewhat different. Similar observations have been reported by earlier researchers (Vanapalli et al., 1998; Miller et al., 2002) and may be attributed to different definitions and philosophies proposed by the researchers for computing these parameters. It can also be noted that, for the same soil with different dry unit weights, when the same fit is used, the variation in the fitting parameters is insignificant. This indicates that there is not much influence of the dry unit weight of the soil on the SWCC. These trends are similar to those reported in the literature (Box and Taylor, 1962; Campbell and Gardner, 1971; Tinjum et al., 1997; Thakur et al., 2004). A critical comparison of the AEV and w_r for samples with similar dry unit weight (e.g., Sample B and Sample H) indicates that AEV for the white clay is quite high as compared to the silty soil. This is consistent with the fact that clays exhibit a higher AEV than silty soils (Tinjum et al., 1997; Miller et al., 2002). Based on this observation, the suction data for the silty soil (Samples A, B, C, D and E) and the white clay (Samples F, G and H) were used simultaneously for developing the SWCCs depicted in Figure 4, using SoilVision 3.34. The values of various parameters used in the fits are presented in Tables 5 and 6 for the silty soil and white clay, respectively. It can again be noted that all parameters, in particular, AEV and w_r, match well with those obtained for the individual samples. This also indicates that SWCC and suction properties of the soil are essentially independent of the dry unit weight.

Table 3. Experimental results for the silty soil

Sample									
A		B		C		D		E	
ψ (Mpa)	w (%)	ψ (MPa)	w (%)	ψ (MPa)	w (%)	ψ (MPa)	w (%)	ψ (MPa)	w (%)
0.12	25.2	0.02	30	0.06	28.3	0.10	24.8	0.21	23.4
0.57	21.2	0.08	27.6	0.32	22.7	0.27	24.3	0.58	21.8
0.92	19.8	1.73	20.9	1.89	16.5	0.31	24.1	0.90	20.2
1.50	16.7	1.77	19.6	2.41	15.3	0.59	21.4	1.53	19.6
1.73	15.7	1.82	16.3	2.78	14.1	0.73	20.4	1.91	19.1
8.07	11.1	2.15	15.5	2.92	12.1	0.82	20.3	2.07	17.6
8.27	10.9	5.82	15.4	5.88	9.6	1.10	20.2	2.91	15.3
11.50	10.6	6.62	14.3	27.40	8.3	1.52	18.9	4.51	14.8
14.80	10.2	8.32	11.9	35.50	7.9	2.53	17.2	5.11	14.3
21.10	8.9	9.04	11.8	43.50	7.8	3.73	16.6	6.14	14.2
23.20	8.9	14.10	11.1	68.00	7.6	4.04	15.3	7.86	12.2
24.90	8.9	43.40	9.4	71.50	7.6	10.20	13.3	12.01	12.1
34.70	8.6	54.50	8.9	80.10	7.6	14.70	12.7	21.20	11.7
66.50	8.3	68.90	8.4	–	–	25.20	11.8	41.10	9.7
72.50	8.0	76.60	8.1	–	–	78.12	8.1	82.10	8.2
80.10	7.9	80.30	7.4	–	–	–	–	–	–

Table 4. Experimental results for the white clay

Sample					
F		G		H	
ψ (MPa)	w (%)	ψ (MPa)	w (%)	ψ (MPa)	w (%)
0.18	25.7	0.32	23.8	0.30	24.7
0.57	24.8	3.14	20.9	1.44	23.5
2.23	20.8	4.93	20.1	2.38	21.6
4.68	15.1	6.46	13.6	3.56	19.5
7.35	13.0	21.60	8.7	3.80	17.1
8.03	11.9	33.70	8.3	4.35	15.3
10.11	11.3	42.70	7.6	4.82	14.5
16.00	10.0	44.60	7.2	5.42	13.5
23.30	9.6	63.30	6.3	6.91	13.4
32.10	9.0	67.10	5.7	18.03	9.5
49.01	7.0	79.10	5.2	42.50	9.3
66.70	6.3	–	–	57.70	7.1
81.00	6.1	–	–	81.20	6.5

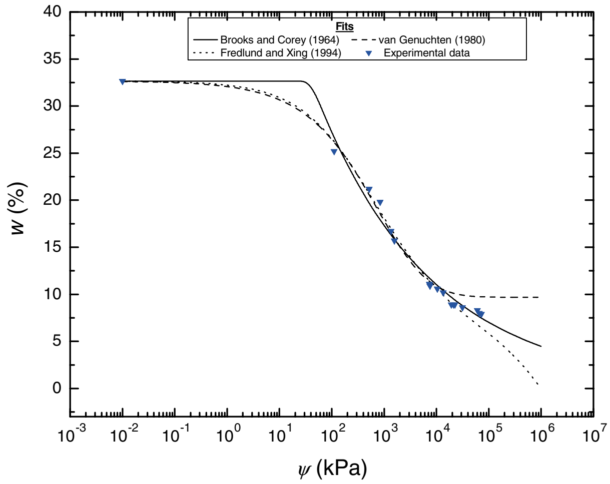

Figure 3. SWCCs for sample A obtained from different fits.

5.1. ESTIMATION OF THE SWCC

SoilVision 3.34 was also used for estimating the SWCCs for the silty soil and the white clay, as depicted in Figure 5, without using the experimental data and with the help of available PTFs (Arya and Paris, 1981; Rawls and Brackensiek, 1985; Tyler and Wheatcraft, 1989; Scheinost et al., 1996; Fredlund et al., 1997). For the sake of comparison and checking the efficiency of individual PTFs, the experimental data for all samples have also been superimposed along with the estimated SWCCs. It can be

Table 5. Details of the parameters used for developing SWCC for the silty soil

Fit	Parameter	Sample A	B	C	D	E	All samples
Fredlund and Xing (1994)	a_f (kPa)	226.72	381.94	165.35	733.74	456.09	332.91
	n_f	0.64	0.54	0.74	0.44	0.49	0.54
	m_f	1.15	1.28	1.02	1.62	1.42	1.29
	h_r (× 10^5 kPa)	8.71	8.88	8.62	8.88	8.88	8.79
	Error	0.9977	0.9976	0.9972	0.9980	0.9980	0.9978
	w_r (%)	0.28	0.28	0.29	0.30	0.28	0.29
	AEV (kPa)	25.68	26.69	26.96	20.46	22.36	23.10
van Genuchten (1980)	a_{vg} (× 10^{-5} kPa^{-1})	6.94	5.32	15.65	1.01	5.58	6.03
	n_{vg}	0.55	0.53	0.63	0.41	0.46	0.48
	m_{vg}	5.02	4.27	4.18	6.11	3.87	4.21
	Error	0.9778	0.9790	0.9757	0.9829	0.9784	0.9745
	w_r (%)	0.29	0.29	0.29	0.29	0.29	0.29
	AEV (kPa)	30.58	40.06	37.24	17.17	19.88	22.37
Brooks and Corey (1964)	a_c (kPa)	39.53	39.13	28.95	28.06	43.93	34.85
	n_c	0.19	0.17	0.19	0.15	0.17	0.17
	Error	0.9865	0.9589	0.9805	0.9734	0.9745	0.9342
	w_r (%)	0.14	0.03	0.01	0.01	0.03	0.01
	AEV (kPa)	39.10	38.74	28.76	27.87	43.78	34.17

Table 6. Details of the parameters used for developing SWCC for the white clay

Fit	Parameter	Sample F	G	H	All samples
Fredlund and Xing (1994)	a_f (kPa)	1603.97	2499.88	2499.91	2500
	n_f	0.65	0.56	0.59	0.57
	m_f	1.67	1.92	1.91	1.96
	h_r (× 10^5 kPa)	8.37	8.04	8.36	8.20
	Error	0.9998	0.9988	0.9999	0.9998
	w_r (%)	0.29	0.29	0.30	0.29
	AEV (kPa)	132.74	123.76	142.28	127.98
van Genuchten (1980)	a_{vg} (× 10^{-5} kPa^{-1})	2.79	2.29	3.71	2.80
	n_{vg}	0.68	0.70	0.71	0.68
	m_{vg}	6.65	6.46	5.40	6.19
	Error	0.9655	0.9590	0.9669	0.9630
	w_r (%)	0.29	0.29	0.29	0.29
	AEV (kPa)	169.95	242.05	203.05	182.96
Brooks and Corey (1964)	a_c (kPa)	121.17	147.79	162.65	142.33
	n_c	0.23	0.23	0.21	0.22
	Error	0.9584	0.8951	0.9079	0.8927
	w_r (%)	0.04	0.05	0.01	0.01
	AEV (kPa)	119.82	144.54	159.83	142.23

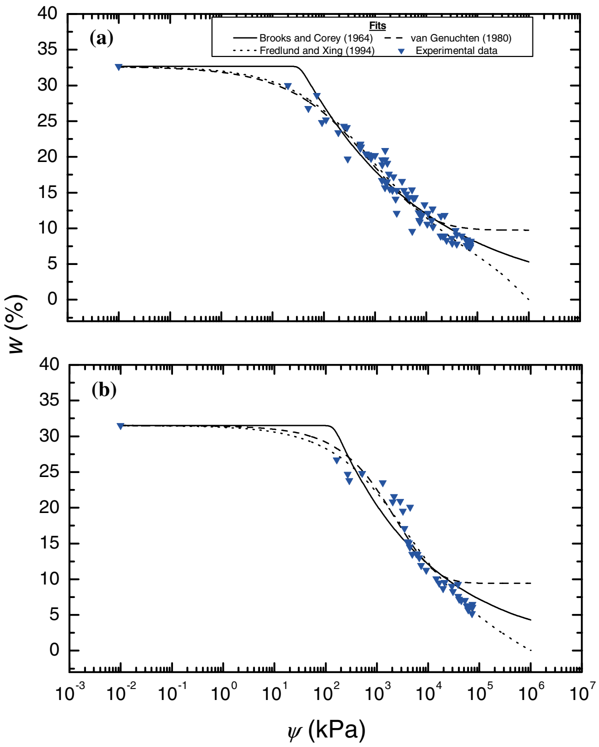

Figure 4. SWCCs for the (a) silty soil and (b) white clay obtained from different fits (combined data).

noted from Figure 5 that only the Fredlund et al. (1997) PTF yields a SWCC, which matches quite well with the experimental results for the two soils used in the present study. Table 7 presents a summary of the AEVs obtained from different PTFs and Fredlund and Xing (1994) fit. The AEVs of the silty soil and the white clay obtained from Fredlund and Xing (1994) fit and Fredlund et al. (1997) PTF match very well.

It can also be noted from Figure 5, that in general the PTFs proposed by Arya and Paris (1981), and Scheinost et al. (1996), underestimate ψ for the same w, for the two soils. The PTF proposed by Rawls and Brackensiek (1985) yields a poor SWCC for the silty soil. However, for the white clay and for the range of $\psi < 3000$ kPa, the Rawls and Brackensiek (1985) PTF was found to yield SWCC, which is quite close to the experimental results. Similarly, the PTF proposed by Tyler and Wheatcraft (1989) was observed to underestimate SWCC for the silty soil. However, for white clay for the range of $\psi < 200$ kPa, Tyler and Wheatcraft (1989) PTF was found to reasonably match the experimental results.

6. Concluding Remarks

The study highlights that the Brooks and Corey (1964) and Fredlund and Xing (1994) fitting functions are valid for extremely high ranges of suction for the

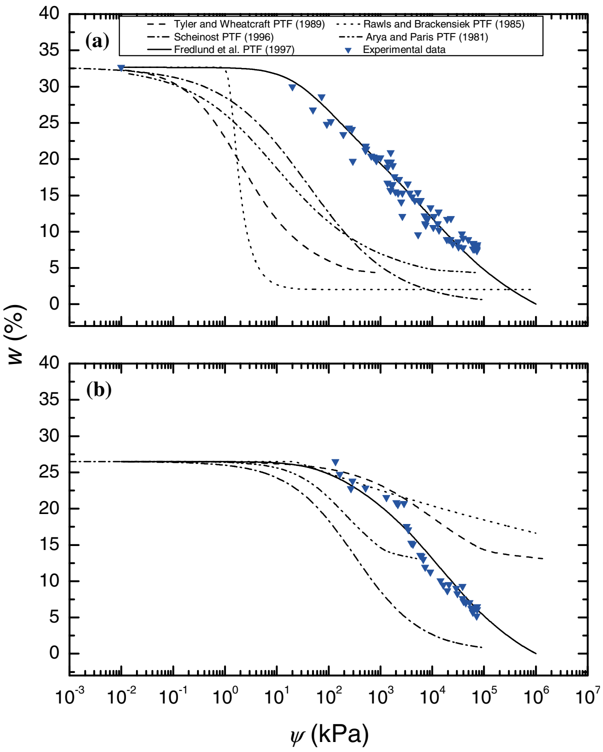

Figure 5. Estimated SWCCs for the (a) silty soil and (b) white clay obtained from different PTFs (combined data).

Table 7. AEVs obtained from different PTFs and Fredlund and Xing (1994) fit

PTF/Fit	AEV (kPa)	
	Silty soil	White clay
Tyler and Wheatcraft (1989)	0.18	263.89
Rawls and Brackensiek (1985)	1.20	12.19
Scheinost et al. (1996)	9.17	173.22
Arya and Paris (1981)	0.27	19.43
Fredlund et al. (1997)	23.40	141.87
Fredlund and Xing (1994) fit	20–27	123–142

fine-grained soils, in general. Whereas the van Genuchten (1980) fitting function is found to be valid only for $\psi < 20$ MPa. It was noted that the dry unit weight of the soil does not have any significant influence on its suction and hence the SWCC. It has also been found that for the white clay, the AEV is much higher than for the silty soil. These observations are consistent with the results reported in the literature. The study also reveals that the PTF proposed by Fredlund et al. (1997) yields a reasonably good estimate of the SWCC for the silty soil as well as the white clay.

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