Water Retention Characteristics of Swelling Clays

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ABSTRACT: Initial state of soil (viz., slurried, intact or compacted state) influences the soil water retention characteristics (SWRC), which in turn affects the unsaturated soil behaviour. Few studies have investigated the effect of initial state of soil on their SWRC, and such studies are rare for swelling clays. In this context, drying- and wetting- path SWRCs have been developed, in the present study, for intact and reconstituted specimens of swelling clays, by employing Dewpoint Potentiometer (WP4C®) and Environmental Chamber in tandem. The wetting-path SWRC has also been developed by controlled water sprinkling method. From the study, influence of initial water content has been observed to be higher on drying-path SWRCs as compared to wetting-path SWRCs of the clays. Further, the drying-path SWRCs for intact and reconstituted specimens converge beyond certain stage of drying. The study suggests the utilisation of reconstituted specimens for studying behaviour of intact clays in relatively dry state.

KEYWORDS: Intact and reconstituted states, Soil-water retention characteristics, Initial state of soil, Drying- and wetting- paths, Swelling clays, Dewpoint Potentiometer

1. INTRODUCTION

Swelling clays exhibit significant volume changes during drying- and wetting- cycles. The soil water retention characteristics (SWRC) are quite useful for understanding the behavior of these clays, especially in its unsaturated state. The SWRC can be defined as the relationship between suction, ψ, and water content, w. The SWRC may not be unique for a soil and depends on various factors such as particle size distribution and mineralogy of soil, fabric structure and pore-size distribution, the path of water movement (drying- or wetting- path) and number of cycles of wetting and drying (Likos and Lu, 2002; Pham et al. 2005; Fredlund et al. 2011; Jayanth et al. 2012). Some studies have also observed the effect of initial state of soil, viz., water content, void ratio and stress history on the SWRC (Delage and Lefebvre, 1984; Tinjum et al. 1997; Vanapalli et al. 1998, 1999; Charles and Pang 2000a, 2000b, Kawai et al. 2000; Miller et al. 2002; Marinho, 2005; Sreedeep and Singh, 2005; Thakur et al. 2005, 2006; Iyer et al. 2013). The effect of applied stress-path on the SWRC has been reported by Pham et al. (2008) and it was noted that the SWRC for initially slurried and undisturbed specimens appears to converge beyond suction of about 1 MPa. The influence of water repellency on soil water retention behavior, viz., movement of water in soil and water entry pressure (Wallach, 2010; Jordan et al., 2015), has been reported by some researchers. Romero et al. (1999) has concluded that the drying- and wetting- path SWRCs depends on dry density of soil for water content above 15%. However the dependence of SWRC on dry density was not observed for water content below 15%. Further, they noted that the drying- and wetting- paths SWRCs converge below water content of 5%. Although these studies provide some insight into the SWRCs of soil in different compaction states (viz., compacted, reconstituted or slurried, intact etc.), such studies on SWRC for swelling clays are rare, and the applicability of these inferences for swelling clays needs to be ascertained.

Amongst different factors, the hysteresis between the drying-and wetting- path SWRCs is one of the important factor affecting the SWRC. Fredlund and Rahardjo (1993) have noted that although hysteresis is a well-known fact, it is not fully understood. Earlier studies have identified the various factors affecting hysteresis between the drying- and wetting- path SWRCs such as air entrapment in the pores, tortuosity and discontinuity in the pore-paths, difference in the contact angles during drying- and wetting-cycles, ink bottle effect and differential shrinkage or swelling in soils (resulting in geometric non-uniformity of pores), etc. (Haines, 1930; Maqsoud et al. 2004; Pham et al. 2005; Jayanth et al. 2012). Another study has reported that the entrapped air during wetting process can occupy between 5 to 15 % of volume of soil mass, hence inducing hysteresis in the suction-water content relationship between the drying- and wetting-paths (Pham et al., 2003).

Experimental studies by some researchers noted that the wetting-path contact angles in sandy soil can be about 20° to 30° higher than the drying-path contact angles (Letey et al., 1962; Laroussi and DeBacker, 1979; Kumar and Malik, 1990). Studies by Mohammad and Sharma (2007) revealed that the hysteresis between the drying- and wetting- path SWRCs is higher for dynamic water flow conditions in comparison to static water flow in soil. The role of hysteresis on influencing the water flow and solute transport in partially saturated media (viz., soil) has been highlighted by Simunek et al. (1999) based on study of earlier literature. The researchers have also highlighted the difficulty in quantification of hysteresis associated with suction-water relationship during the drying- and wetting- paths. These studies indicate that few research efforts have addressed the hysteresis associated with the water retention characteristics of soils, and not much attempt has been done to understand the hysteresis associated with SWRCs of swelling clays. It is opined that such studies would provide insight into the engineering behavior of swelling clays when subjected to cycles of drying and wetting. In this context, this study focuses on establishing the drying- and wetting- path water retention characteristics as well as hysteresis associated with these paths, for swelling clay specimens dried from initial intact and reconstituted (read slurried) states.

2. EXPERIMENTAL INVESTIGATIONS

2.1 Soil Properties

Three naturally occurring swelling clays (designated as SC1, SC2 and SC3) collected from western part of India were considered in the present study. These clays were characterized to establish their physical and mineralogical properties. The grain size distribution (ASTM D 422-94), consistency limits (ASTM D 4318-05; ASTM D 427-98) and specific gravity G_s (ASTM D 5550-06) of these clays were determined, and the results are presented in Table 1. The soils can be characterized as CH as per the Unified Soil Classification System (ASTM D 2487-06e1). Further, the free swell Index, *FSI*, (IS: 2720 Part XL, 2002) of the clays SC1, SC2 and SC3 were observed as 130%, 70% and 63%, respectively. The specific surface area, *SSA*, of the clays was determined by conducting Ethylene Glycol Monoethyl Ether Absorption (EGME) tests, based on the recommendations available in the literature (Arnepalli *et al.* 2008). *SSA* values of 303, 324 and 311 m^2/g were obtained for clays SC1, SC2 and SC3, respectively. The mineralogical composition of the clays were determined with the help of X-ray Diffraction (XRD) Spectrometer (PANalytical X'Pert PRO), which employs a graphite monochromator and Cu-Kα radiation. The clay specimens were scanned from 2θ ranging from 5° to 80°. The major minerals present in these clays were quartz and montmorillonite. The properties of the intact samples of the clays (in-situ properties) are presented in Table 2. The presence of montmorillonite mineral and relatively high SSA and FSI values confirm the swelling (viz., expansive) nature of soils.

Table 1 Physical Characteristics of the clay samples

Sample	G	(%)			Atterberg Limits (%)				
		Sand	Silt	Clay	w_l	w_p	I_p	w_s	I_s
SC1	2.62	05	25	70	114	22	92	16	06
SC2	2.57	04	15	81	111	28	83	17	11
SC3	2.76	48	14	38	60	19	41	16	03

w_l = liquid limit, w_p = plastic limit, I_p = plasticity index, w_s = shrinkage limit, I_s = shrinkage index

Table 2 In-situ characteristics of the intact clay samples

Sample	Depth (m)	w (%)	e_0	γ_b (g/cc)	γ_d (g/cc)	w_s (%)
SC1	20	42	0.87	1.99	1.40	33.2
SC2	25	40	1.02	1.78	1.27	39.7
SC3	30	40	1.24	1.72	1.23	44.9

w = in-situ water content, e_o = in-situ void ratio, γ_b = in-situ bulk density, γ_d = in-situ dry density, w_s = saturation water content

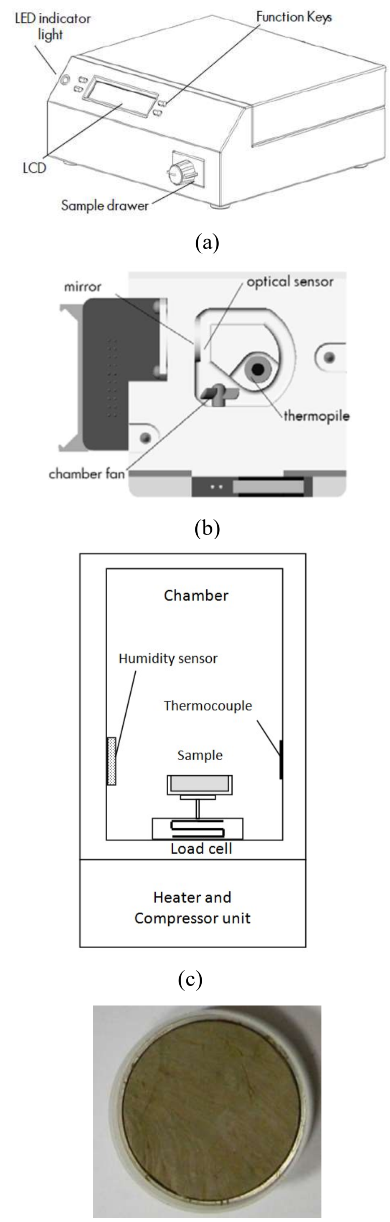
2.2 Establishment of SWRC

The suction measurement of the specimens were carried out by employing Dew point Potentiameter (WP4C®). Figure 1(a) shows the schematic of WP4C®, and the block chamber within WP4C® depicted in Figure 1(b) consists of a mirror, dew point sensor (photodetector cell), a temperature sensor (thermopile), an infrared thermometer (optical sensor) and a fan. The dew formation on the mirror is detected with help of a photodetector cell, which senses the change in the reflectance of an infrared beam of light, the thermopile detects the temperature of the air and the infrared thermometer measures the temperature of the specimen. The soil specimen placed in the sampling cup, is equilibrated with the air in the headspace of the specimen chamber for its relative humidity. For attaining faster equilibrium, a fan is also provided inside the block chamber. At equilibrium, the water potential of air in the chamber is same as the water potential (viz., suction, ψ) of the soil specimen. The inbuilt software converts the water activity, a_w (i.e., the relative humidity of the specimen) into ψ by employing the Kelvin's equation (Thomson 1870, 1871) represented by Eq. 1, and displays on the LCD panel the suction of the soil specimen, in MPa or pF and the temperature of the soil specimen.

$$\psi = \frac{R'T}{M}\ln(a_w) \tag{1}$$

where R' is the universal gas constant (=8.31 J/mol.K), T is the temperature of the specimen in K, M is the molecular mass of water (=18), a_w is the water activity, which is equal to the ratio of the vapor pressure of air and the saturation vapor pressure.

To establish the drying-path SWRC of natural clays, undisturbed (intact) clay specimens were extracted, by using cylindrical stainless steel rings with cutting-edge of diameter 35.5 mm and height 7 mm, from undisturbed Shelby tube samples of swelling clays collected from western part of India. The extracted specimens with rings were placed in the plastic containers provided by manufacturer of dewpoint potentiometer, WP4C®, (Jayanth et al. 2012, Iyer et al. 2013) and the specimens were subsequently saturated by employing an environmental chamber (refer Figure 1(c)) at 27±1 °C and 95±2 % humidity for a period of about 2 weeks. The end of possible saturation was indicated by negligible change in weight of the specimen or constant suction values for three consecutive readings measured at time interval of 24 hours. The initial suction after saturation was measured by WP4C®. Figure 1(d) depicts photograph of intact clay specimen used for suction measurement using WP4C®.



(d)

Figure 1 (a) Schematic view of WP4C® (b) Details of the block chamber (WP4C User's Manual, 2010) (c) Environmental Chamber for wetting of samples (d) Undisturbed clay specimen for suction measurement in WP4C®

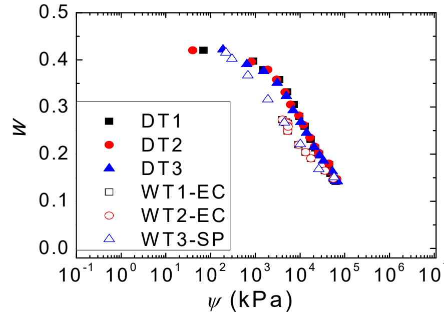
The specimens were subsequently subjected to air-drying, and their suction was measured at different stages of drying. The end of air-drying cycle was indicated by negligible change in weight of the specimen or constant suction values for three consecutive measurements at time interval of 24 hours. The specimens were weighted, at each stage of drying, to compute the water content of the specimens. The relationship of suction and water content was plotted to obtain the soil water retention curve, SWRC of the intact clay specimens.

After air-drying of the specimens, the wetting tests were conducted on these specimens, by placing them in environmental chamber at 27±1°C and 95±2 % humidity and subsequently determining the water content and suction at different stages of wetting. Wetting tests were also conducted by water sprinkling method, as explained herein. In this method, during each step of wetting, about 0.15 ml of distilled water was sprinkled uniformly on the clay specimen in form of droplets by using 1 ml micropipette (least count 0.01 ml, manufactured by Gibson). The specimens were then sealed in air-tight environment by closing the specimen containers with cap, covering them by plastic sheet and storing in a closed desiccator and kept for 48 hours to achieve equilibration. Subsequently, for suction measurement, the specimens were weighted and placed in the WP4C®. This procedure was repeated until specimen water content reaches the saturation water content. This method represents the wetting of clay specimen through flooding / inundation during rainfall or infiltration of water in clayey soil. The wetting-path SWRCs of the specimens were established similar to drying-path SWRCs, by plotting the suction-water content relationship.

After completion of the wetting tests for the intact specimens, the specimens were air-dried and then pulverized carefully with the help of mortar and pestle to break the aggregation and utilized for establishing the SWRC of the reconstituted specimens as explained in the following. The reconstituted clay specimens were prepared with the initial moisture content close to the *LL* of the clayey soil (viz., slurried specimens), as suggested from earlier studies (Jayanth *et al.* 2012, Iyer et al. 2013). The slurried clay specimens were stored in polythene bags in a closed container for 24 hours and subsequently poured into the PVC cups (provided by the manufacturer of WP4C®) to obtain a homogeneous specimen of about 5 mm thickness (WP4C® manual, 2010, Jayanth et al. 2012). The process of establishing drying- and wetting- path SWRCs for the reconstituted specimens is similar to that of intact specimens as explained above. It may be noted that for intact specimen T1 (viz., trial T1) of clay SC1, three cycles of wetting and drying was conducted. Hence the reconstituted specimen T1 was prepared only after completion of three cycles of drying- and wetting- tests on intact specimen T1.

3. RESULTS AND DISCUSSION

Figures 2 to 4 depict the drying- and wetting- path SWRCs for specimens of swelling clays SC1, SC2 and SC3 dried from intact and reconstituted states. In the figures, 'D' indicates drying cycle; 'W' indicates wetting cycle; 'T1', 'T2' and 'T3' indicates trials. 'EC' indicates that wetting test was conducted by employing the environmental chamber, whereas 'SP' indicates that wetting was done by controlled water sprinkling method. From these figures, it can be noted that the wetting path by two different methods (viz., hydraulic wetting in the environmental chamber and mechanical wetting by controlled water sprinkling) trace similar paths. Here hydraulic wetting indicates natural ingress of water in clay whereas mechanical wetting indicates ingress of water assisted by gravity flow. This suggests that for the specimens considered in this study, irrespective of the method of wetting employed (hydraulic wetting or mechanical wetting), the wetting-path is similar. However, as expected, the mechanical wetting results in overall higher final water content of the specimens. Figure 3(a) depicts the water ingress for specimens of clay SC2 during hydraulic wetting. It can be noted that it was not possible to achieve full saturation of the specimens by hydraulic wetting, as this process stops once the water vapor equilibrium between the specimens and surrounding atmosphere is achieved. Full saturation of specimens was achieved only during the mechanical wetting, wherein the water ingress into the pores might have been achieved by diffusion and redistribution of water (assisted by gravity flow) in the clay specimen. It must be noted that for all the



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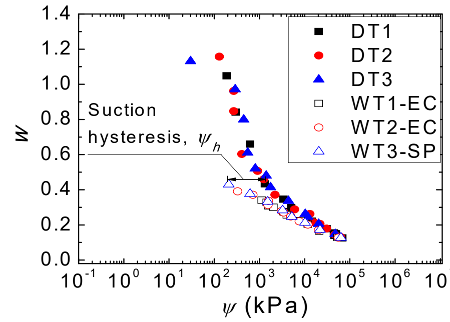
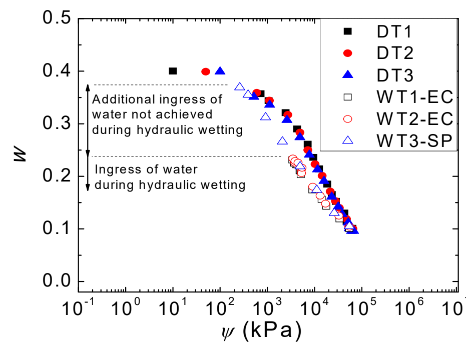


(b)

Figure 2 Drying- and wetting- path SWRCs for the clay SC1 dried from (a) Intact state, and (b) Reconstituted state



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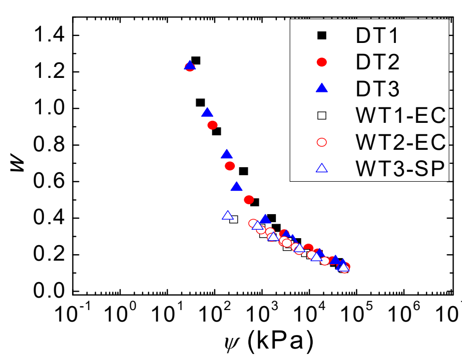
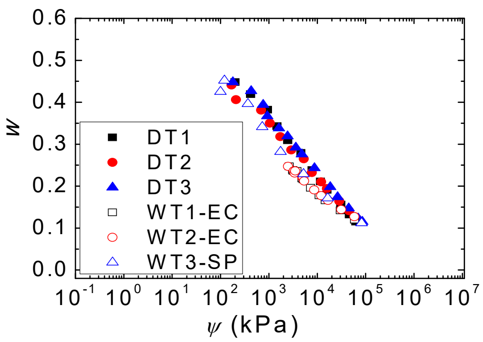


(b)

Figure 3 Drying- and wetting- path SWRCs for the clay SC2 dried from (a) Intact state, and (b) Reconstituted state specimens, mechanical wetting by controlled sprinkling method was terminated once full saturation was achieved (saturation water content, w_s, is presented in Table 2). Further, it can also be observed from Figures 2 to 4, that the water ingress during hydraulic wetting is lower for intact specimens as compared to the reconstituted specimens. This might be attributed to difference in the pore size distribution of the intact and reconstituted specimens at the end of hydraulic wetting cycle. However, microstructure studies are required on specimens along the wetting-path to identify the critical pore size which inhibits the hydraulic wetting in clays.



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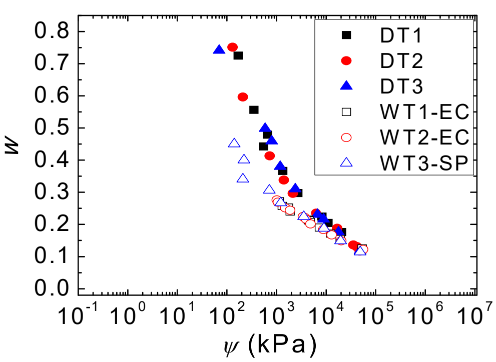


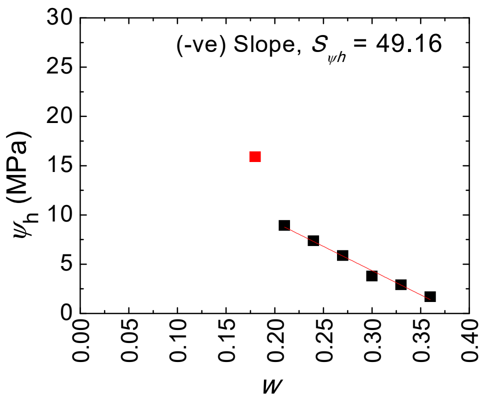
(b)

Figure 4 Drying- and wetting- path SWRCs for the clay SC3 dried from (a) Intact state, and (b) Reconstituted state

From these figures, the hysteresis between the drying- and wetting- path SWRCs can also be observed for both intact and reconstituted specimens of clays SC1, SC2, and SC3. The hysteresis during drying and wetting processes in clays has been attributed to various factors such as air entrapment in the pores, geometric non-uniformity of pores, discontinuity in the pore-structure and tortuosity in the pore-paths, clay mineralogy, difference between contact angle during drying- and wetting- cycles, etc (Haines 1930; Likos and Lu, 2002; 2004; Pham et al. 2005, Jayanth et al. 2012, Iyer et al. 2013).

For swelling clays, the mineralogy also plays an important role in hysteresis during drying- and wetting- paths due to the differential shrinkage and swelling associated with swelling clays, which would result in non-uniform pore-size distribution of soil, discontinuity of pores and tortuous paths of the connected pores. Some earlier studies have attributed the differential volume change behavior of soils with active mineralogy during drying- and wetting- cycles to the irreversible work done during the swelling process (Barrer et al., 1953; Lal and Shukla, 2004).

To quantify the hysteresis associated with the drying- and wetting- path SWRCs, "suction hysteresis", ψ_h, (refer Figure 2b) has been defined as the difference in suction between the drying- and wetting- paths at a particular water content. The variation of suction hysteresis, ψ_h, with water content, w, has been plotted in Figures 5 and 6 for intact and reconstituted specimens of clays SC1, SC2, and SC3. The slope of the plot indicates the variation of suction hysteresis at different degree of saturation. From the figures, it can be observed that ψ_h is higher during beginning of wetting cycle (low water content), which may be attributed to entrapped air as well as initial resistance to wetting owing to difference in contact angles during wetting and drying cycles. Cary (1967) had opined that the portion of entrapped air would get removed by either diffusion or redistribution of water during further wetting process. Another study had suggested that the difference between contact angles during drying and wetting cycles would reduce as the wetting progresses (Bessel, 1959). These inferences indicate that ψ_h is expected to reduce as degree of saturation increases during further wetting process, as observed in this study.



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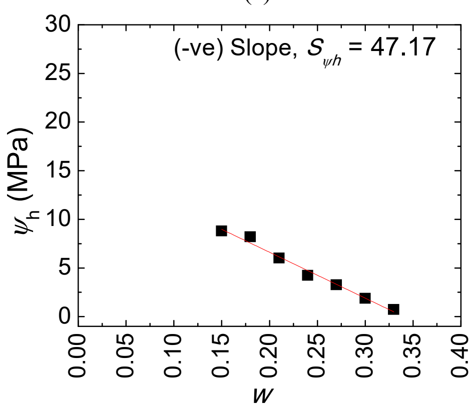

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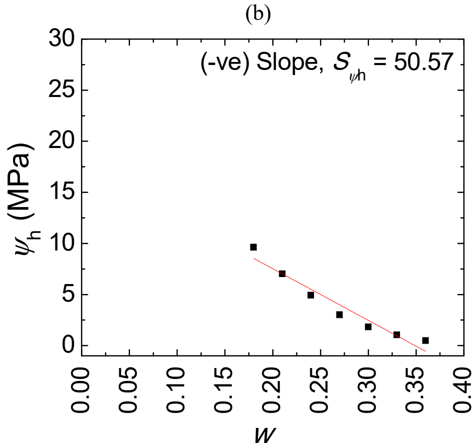

(c)

Figure 5 Variation of Suction hysteresis with water content for the intact specimens of the clays (a) SC1, (b) SC2, and (c) SC3

Further, from Figures 5 and 6, it can also be observed that the slope of ψ_h vs. w is higher for intact specimens as compared to the reconstituted specimens. This suggests that for reconstituted specimens, after initial higher ψ_h, the resistance to wetting eases out more gradually in comparison to the intact specimens. The residual suction hysteresis at the end of wetting cycle may be attributed to the residual entrapped air.

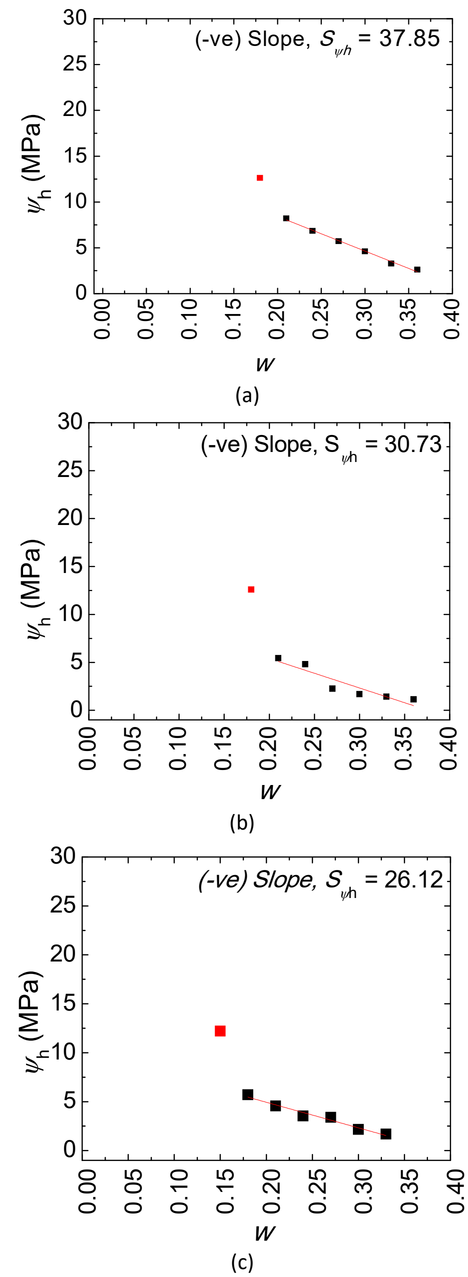

Figure 6 Variation of the suction hysteresis with water content for the reconstituted specimens of clays (a) SC1, (b) SC2, and (c) SC3

Figures 7a, 8a and 9a depict the comparison of drying-path SWRCs for intact and reconstituted specimens of clays SC1, SC2 and SC3. It can be observed from the figures that for all the clays, the SWRCs for intact and reconstituted specimens converge beyond certain suction, defined as critical suction, ψ_c (Iyer et al., 2017) . The value of ψ_c for clays SC1, SC2 and SC3 are observed to be 2 MPa, 2.5 MPa and 1.4 MPa, respectively. The convergence of drying-path SWRCs for intact and reconstituted specimens of clays, beyond the critical suction, ψ_c, (ranging from 1.4 MPa to 2.5 MPa in this study) can be attributed to either convergence of pore size distribution of the intact and reconstituted specimens, which influences major portion of the drying- path SWRC, or ceasing of the effect of clay microstructure on the SWRC, beyond the critical suction. In this line, Iyer et al. (2017) have studied the microstructure of swelling clay dried from initial intact and reconstituted states and observed the convergence of microstructure of air-dried intact and reconstituted specimens of same clayey soil. Incidentally, Tuller and Or (2005) have reported that capillary component of suction becomes insignificant beyond suction of 10 MPa and the suction is governed by adsorptive forces. However, these observations were based on studies related to sand, sandy loam, silty loam and silty clay soils, and such inferences for swelling clays needs further study.

Further, Figures 7b, 8b and 9b depict the wetting-path SWRCs for intact and reconstituted specimens of clays SC1, SC2 and SC3. It can be observed that the wetting-paths are quite comparable for the intact and reconstituted specimens of the clays. This suggests that the air-dried specimens of the intact and reconstituted specimens with comparable pore size distribution (Iyer et al. 2017), when subjected to wetting cycle, swells and follows similar paths for the intact and the reconstituted specimens. Further, the wetting-paths appear to somewhat deviate below suction of 1 MPa. This may be attributed to differences in the entrapped air for intact and reconstituted specimens which tends to create differences in the suction at relatively higher water content. Tarantino (2009) had similar inferences along the wetting-path for compacted and reconstituted specimens of clay.

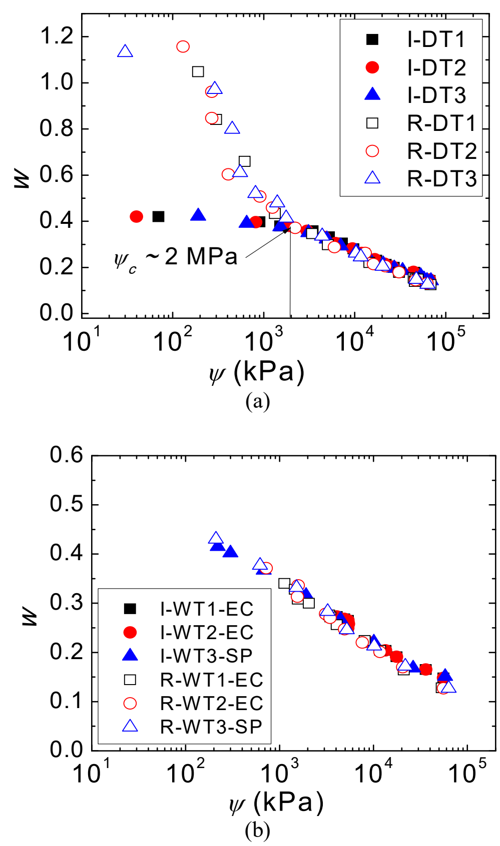

Figure 7 Comparison of SWRCs for the Intact and Reconstituted specimens of the clay SC1 during (a) Drying-path, and (b) Wetting-path

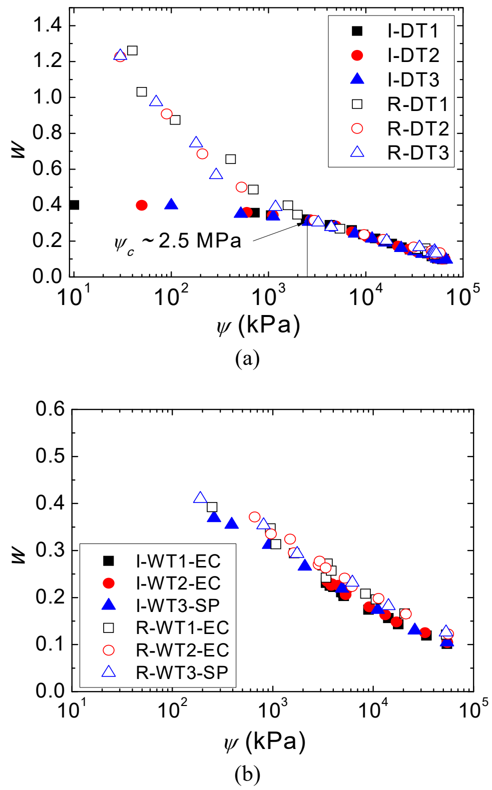

Figure 8 Comparison of SWRCs for the Intact and Reconstituted specimens of the clay SC2 during (a) Drying-path, and (b) Wetting-path

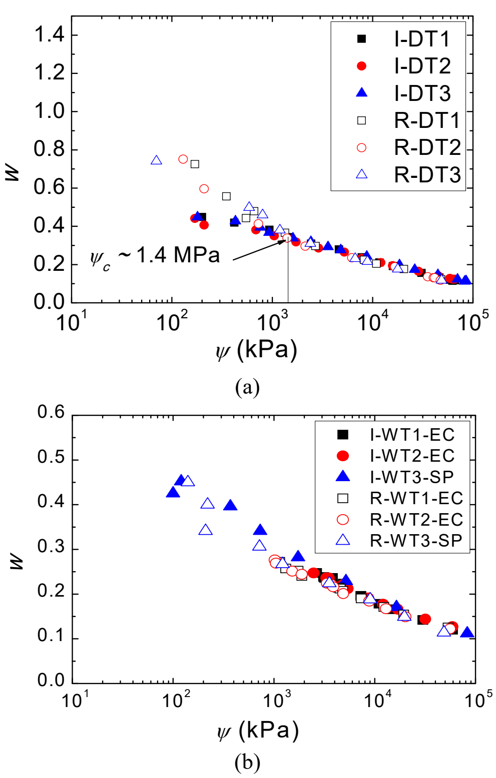

Figure 9 Comparison of SWRCs for the Intact and Reconstituted specimens of the clay SC3 during (a) Drying-path, and (b) Wetting-path

Further, to quantify the difference in SWRC for intact and reconstituted specimens, the drying- path SWRC parameter, ψ_a (air entry suction) was obtained from Fredulund Xing (FX) Fitting function by employing the Soil-Vision 4.21 database (2005). FX fit has been observed to provide reasonably good fit for drying-path SWRCs (Thakur et al., 2006).

The SWRC represented by the FX fit, for suction range of 0 to 10^6 kPa, is:

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

where $w(\psi)$ is the gravimetric water content at any suction, ψ; w_s is the gravimetric water content at saturation; a_f, is the fitting parameter primarily dependent on the air-entry suction, ψ_a (suction at which air enters the soil pores during drying); n_f, is the fitting parameter that is dependent on the rate of extraction of water from the soil beyond the ψ_a; m_f is the fitting parameter, which depends on the residual water content, w_r; and h_r is the suction (in kPa) corresponding to the w_r. It must be noted here that w_r is water content below which there is negligible change in the water content corresponding to an increase in the soil suction. The SWRC fitting parameters a_f, n_f and m_f can be obtained by nonlinear regression procedure (Fredlund and Xing, 1994).

Figure 10 shows FX fit for intact and reconstituted specimens of soil SC1. The reconstitued specimens are marked with "R" and intact specimens with "I" in the figure; "D" indicates drying-path and "T1, T2 and T3" indicates trials. The values of ψ_a are presented in Table 3. It can be observed from the table that ψ_a is lower for reconstituted specimens as compared to intact specimens. This may be attributed to significantly higher void ratio of reconstituted specimen as compared to intact specimen (Iyer et al., 2017). Further, Pham et al. (2005) have suggested that the Feng and Fredlund model (1999) can be employed for fitting the wetting path SWRCs. However, as this model is not available in SoilVision 4.21 database, the wetting-path SWRC fitting curve for reconstituted and intact specimens of soil SC1 have not been compared in this study.

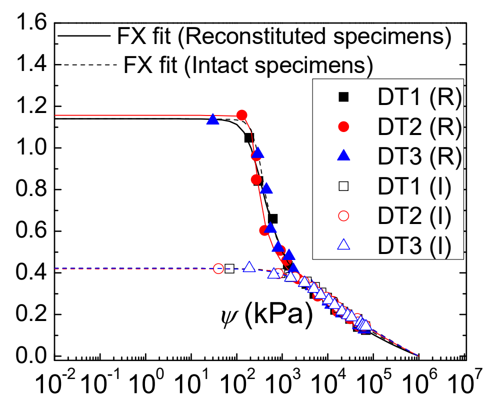

Figure 10 FX fit for drying- path SWRCs for intact and reconstituted specimens of soil SC1

Table 3 Air entry suction from FX fit for drying-path SWRC of the Intact and Reconstituted specimens of soil SC1

Specimen	ψ_a (kPa)			R^2		
	DT1	DT2	DT3	DT1	DT2	DT3
Intact	1187	1233	1034	0.990	0.996	0.996
Reconstituted	150	188	217	0.997	0.991	0.994

To understand the hysteresis upon subsequent cycles of drying and wetting, the intact specimen T1 (Trial T1) for clay SC1 was subjected to two more cycles of drying and wetting, and the SWRCs are depicted in Figure 11. In the figure, 'D' indicates drying cycle; 'W' indicates wetting cycle; 'T1', 'T2', and 'T3' indicates trials; C1, C2, and C3 depict cycles 1, 2 and 3, respectively, and 'EC' indicates hydraulic wetting by employing environmental chamber.

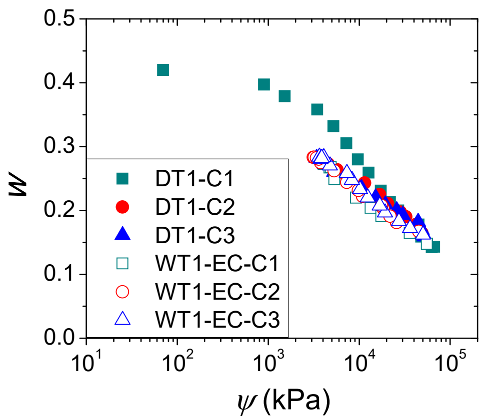

Figure 11 Cycles of drying- and wetting- path SWRCs for specimen (Trial T1) of clay SC1

It can be observed from the figure that drying- and wetting- path SWRCs for 2nd and 3rd cycles scan between the main drying- and wetting- paths (1st drying- and wetting- paths). Further, it can be noted that the hysteresis between drying- and wetting- path SWRCs for 2nd and 3rd cycles are insignificant and the paths coverage towards unique scanning SWRC, which suggests that the built-up of suction during drying cycle is reversible during the wetting cycle. Similar observations were reported by Jayanth et al. (2012), based on the study of reconstituted specimens, wherein it was inferred that after three cycles of drying and wetting, the SWRCs retrace their paths.

Figure 12(a) and (b) depicts the influence of percentage clay content, % *CL* and initial water content of intact specimen, w_i (before drying cycle) on the critical suction, ψ_c. It is observed that 'ψ_c' is lower for higher 'w_i' and 'ψ_c' increases with increase in % *CL* of soil. Further Figures 12(c) and (d) depicts the relationship between initial dry density of intact specimen, γ_d and initial void ratio of intact specimen, e_0 on the critical suction, ψ_c. The influence of γ_d and e_0 on ψ_c is not clearly visible. It appears that the influence of % *CL* and w_i on ψ_c is more evident, which indicates that % *CL* and w_i have more pronounced effect on the changes in pore size distribution (which affects the convergence of SWRCs for intact and reconstituted specimens) during drying than γ_d and e_0. However, as these inferences are only based on three soils, the data set needs to be extended to large number of soils.

The convergence of drying-path SWRCs for intact and reconstituted specimens indicate that the reconstituted specimens can be utilized for understanding processes in intact specimens in relatively dry state. In this context, earlier researchers have reported the importance of water retention curve at dry end (viz., suction beyond the critical suction, ψ_c) in modelling various processes such as biological processes in soil under arid conditions (Ryel et al., 2002; Santamaria and Toranzos, 2003; Jamieson et al., 2002), sorption and desorption of volatile organic compounds within/from geomaterial matrix and their migration within the geomaterial (Jackson, 1964; Grismer, 1987; Konukcu et al., 2004). Some studies have noted that the flow and sorption/desorption processes at dry end is governed by adsorptive processes and vapor flow (Jackson, 1964; Grismer, 1987; Konukcu et al., 2004). Moreover, processes governed by diffusion would be more prominent at dry end and would be controlled by adsorptive processes.

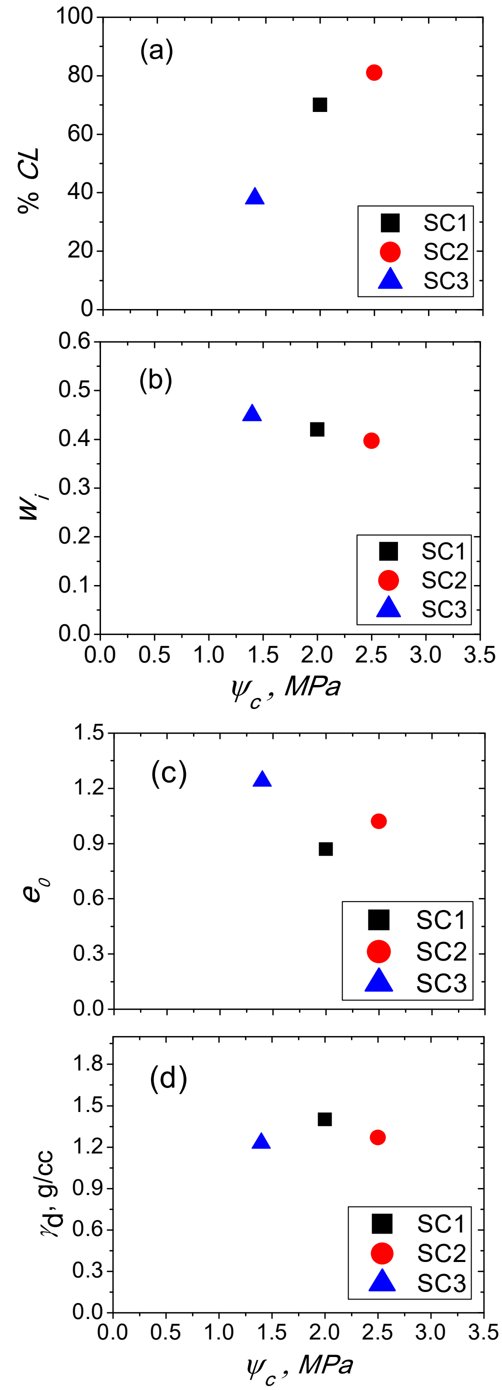

Figure 12 Variation of Critical suction, ψ_c with (a) % *CL*, (b) w_i, (c) e_0, and (d) γ_d, for the clays SC1, SC2 and SC3

4. CONCLUSIONS

The current study was aimed at understanding the water retention behavior of swelling clays in their intact and reconstituted states. Drying- and wetting- path SWRCs were developed with initial intact and reconstituted states for specimens of three different swelling clays. Further, scanning SWRCs were also developed for a intact specimen of swelling clay SC1. The hysteresis between drying- and wetting- SWRCs of the clay specimens was also studied. The following conclusions can be drawn from the study:

1. The primary drying- and wetting- path soil water retention characteristics (SWRC) exhibits hysteresis, for both the intact and reconstituted specimens of swelling clays. It can be inferred that initially higher hysteresis between drying- and wetting- paths (at beginning of wetting cycle attributed to factors such as difference in contact angles and entrapped air) are partially recovered at the end of first cycle of wetting. The residual hysteresis at the end of first wetting cycle can be attributed to residual entrapped air within the soil mass.
2. The study of drying- and wetting- path SWRCs for intact specimen of clay SC1 indicates that after the first cycle, the subsequent scanning drying- and wetting- path SWRCs appear to converge with insignificant hysteresis. The convergence of SWRC to a unique SWRC assumes significance in context of application of SWRC for understanding engineering behavior of swelling clays. It is suggested that more studies be carried out on water retention behavior and microstructural changes for clays subjected to multiple cycles of drying and wetting, to confirm the uniqueness of SWRC.
3. The difference in initial state of clay (viz., intact and reconstituted) specimens has more predominant effect on the drying- path SWRCs as compared to the wetting- path SWRCs. The wetting- path SWRCs appear to nearly trace similar paths for intact and reconstituted specimens. Further, it is observed that beyond a certain critical suction, ψ_c; the drying- path SWRCs converge, which can be attributed to convergence of pore-size distribution and dominance of adsorptive forces on SWRC in comparison to the capillary suction towards end of drying cycle. Further, it has been observed in this study that ψ_c increases with increase in clay content of soil, whereas it reduces with increase in initial water content of the specimen.
4. It is observed in the study that the SWRCs for reconstituted and intact specimens are quite similar in relatively dry state. Hence, the SWRC of reconstituted specimen can be useful for understanding the various processes in relatively dry specimens of natural soils; such as diffusion, vapor flow, sorption/desorption of volatile organic compounds and gases, as well as biological processes within soil in arid regions.
5. It is opined that microstructural studies on specimens along the primary as well as scanning drying- and wetting- paths would yield better understanding of the variation in hysteresis associated with the drying- and wetting- path SWRCs.

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