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Drying and wetting soil-water retention behaviour of a highly expansive clay under varying initial density

Ruan A. Murison[1*], *SW* Jacobsz[1], *Tiago A.V.* Gaspar[2], *Talia S.* da Silva Burke[1], and *Ashraf* S. Osman[3]

[1]University of Pretoria, Department of Civil Engineering, Lynnwood Rd Hatfield 0028, South Africa
[2]University of Sheffield, Department of Civil and Structural Engineering, Mappin St Sheffield S1 3JD, United Kingdom
[3]Durham University, Department of Engineering, Lower Mountjoy Durham DH1 3LE, United Kingdom

Abstract. Expansive (or swelling) clays are the most prolific problem soil across Southern Africa and many parts of the world. Large volume changes due to seasonal wetting and drying cause millions of dollars' worth of damage to engineering infrastructure yearly. Soil-water retention behaviour is dependent on density, and determining the correct retention curve may be key for reliable design of infrastructure. Soil-water retention curves and shrinkage curves were measured for recompacted samples of a highly expansive bentonite clay from South Africa. Four samples were prepared at varying initial dry densities between approximately 1200 and 1500 kg/m^3 and subjected to total suction testing in a dewpoint hygrometer. The water content of each sample was varied through wetting and drying. The sample volume was measured after each suction reading, allowing relationships between suction and void ratio, degree of saturation and water content to be determined. The relationship between gravimetric water content and suction was not significantly influenced by initial density. Degree of saturation at a given suction varied significantly according to initial density. Volume reductions of 25% to 36% from saturated to residual conditions were recorded, and samples tended to a residual void ratio of 0.35 to 0.4. The swelling clay showed propensity for maintaining high suctions (over 300 MPa at residual conditions) and hysteretic response between primary drying and wetting.

1 Introduction

Reports of the presence of expansive soils and the associated consequences at many locations across every continent show that these soils are a worldwide problem [1, 2-6]. Expansive clays are the problem soil responsible for the greatest damage to infrastructure in North America [2, 3], Great Britain [4], Southern Africa [5] and China [6]. To understand the seasonal heaving and shrinkage these clays exhibit and thus limit structural damage, an understanding of unsaturated soil mechanics and the relationships between water content and volume change are vital.

The soil-water retention curve (SWRC) is known to be dependent on sample density [7, 8]. In the case of swelling clays, where density in itself is highly dependent on water content, it becomes challenging to accurately determine the in-situ soil-water retention behaviour from a recompacted specimen. This study aims to gain a better understanding of the volumetric and soil-water retention behaviour of expansive clay present at a selected site near Vredefort, South Africa, with varying initial density. Specific reference to the hysteresis between wetting and drying is highlighted.

2 Unsaturated expansive clays

Expansive clays exhibit large volume changes with changes in water content, potentially causing distress to overlying or adjacent infrastructure. The active clay minerals are generally aluminosilicates in the smectite group, such as montmorillonite [9]. The clay platelets are loosely bonded by polar water molecules, allowing for considerable ingress and expulsion of water during seasonal wetting and drying, causing swelling and shrinkage. This concept is depicted in Fig. 1 (after [10]).

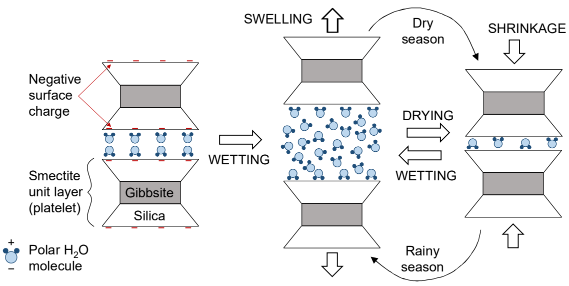

Fig. 1. Microstructural swelling and shrinkage of smectites (after [10]).

Unsaturated soil mechanics concepts are important considerations in understanding the behaviour of swelling clays with varying water contents. Testing of

* Corresponding author: ruan.murison@tuks.co.za

partially saturated soils to predict heaving of swelling clays (for example, the double-oedometer test) has been documented since as early as the 1950s [11].

The term 'retention' curve is preferred to 'characteristic' curve as the relationship between degree of saturation and suction is dependent on factors such as initial void ratio, and as such, is not a 'characteristic' relationship [7]. The dependence of the soil-water retention curve on net stress and initial dry density for recompacted samples has been shown experimentally (for example [8, 12]). An additional challenge arises when the samples inherently experience large changes in density during wetting or drying, as is the case for an expansive soil. Reliable volume measurement for initial conditions and throughout drying and wetting are thus key for the determination of each SWRC and shrinkage curve (SC) of the samples with varying initial densities.

In several software applications, only one primary curve is required for numerical modelling of unsaturated soils (e.g. [13, 14]); usually a drying curve, as these are easier to measure. Hysteresis between wetting and drying primary curves was considered in this study, to support comment on the validity of such an assumption.

3 Soil properties

The selected site near Vredefort, South Africa is underlain by an approximately 6 m thick layer of expansive clay, adjacent to a bentonite mine. Samples taken from a depth of 3 m were considered for this study as this was the material with the highest expansive potential according to the Van der Merwe activity chart [15]. A simplified borehole log is given in Fig. 2.

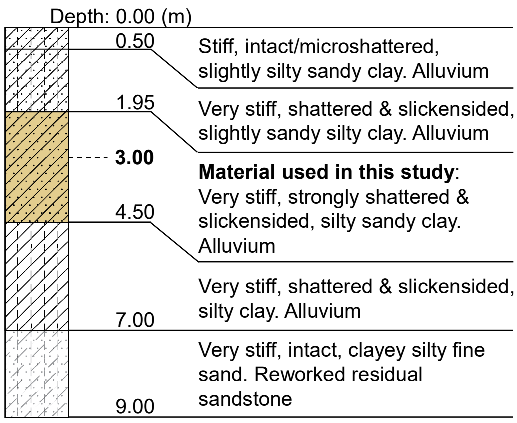

Fig. 2. Simplified borehole log of selected site.

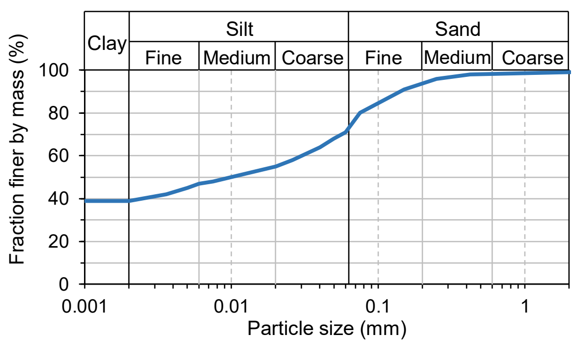

Fig. 3. Grading curve for samples from a depth of 3.0 m.

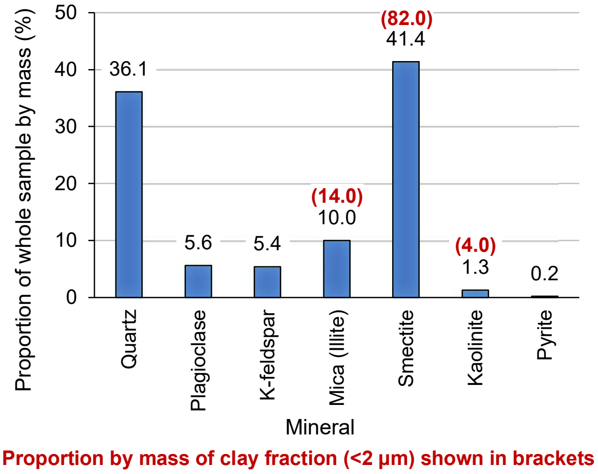

Fig. 4. Mineralogy of the clay sampled at 3.0 m, from XRD.

Fig. 3 gives the particle size distribution of the tested material, and Fig. 4 indicates the mineralogical composition, based on X-ray diffraction (XRD) results. The high smectite content in the clay fraction, paired with the very high plasticity index and activity, motivate the classification of the soil as a very highly expansive clay. Table 1 gives properties of the clay.

Table 1. Properties of the expansive clay sampled at 3.0 m.

Property	Value
Specific gravity, G_s	2.69
In-situ dry density, ρ_d (kg/m^3) *	1450
In-situ void ratio, e *	0.857
In-situ gravimetric water content, w (%) *	21.5
In-situ degree of saturation, S (%) *	67.5
Liquid limit, LL (%)	109
Plastic limit, PL (%)	27
Plasticity index, PI (%)	82
Clay fraction by mass (<2 μm, %)	39
USCS Classification [16]	CV
Activity [17]	2.1
Potential expansiveness [15]	Very high

* sampled during wet season

4 Experimental procedure

Disturbed samples obtained from site were air-dried for at least 30 days before being crushed using a mortar and pestle. Crushed material was subsequently sieved through a 2 mm sieve. Water was added to the air-dried material to achieve a target gravimetric water content corresponding with full saturation at the target dry density for each sample. Samples were statically compacted to various initial dry densities in a precision machined stainless steel compaction mould, which facilitated the preparation of cylindrical samples with initial height of 10 mm and diameter of 15 mm. Undisturbed samples were not considered for this study. However, [1, 18] determined similar hydromechanical behaviour between series of statically compacted and undisturbed oedometer and SWRC samples. The Meter Group WP4C dewpoint hygrometer [19] was used to measure total suction of samples at a set point of 25ºC. Gravimetric water content was continuously varied for each sample, with suction readings taken incrementally to measure the primary drying and wetting curves. A mass balance with a resolution of 0.001 g was used. Samples were allowed to air-dry until the natural minimum water content under the ambient laboratory relative humidity was reached, beyond which drying was facilitated in a desiccation chamber with silica crystals. This allows for samples to be dried out further without subjecting them to elevated temperatures [1]. Wetting was facilitated by placing the samples in a sealed desiccation chamber with distilled water, to create a 100% relative humidity environment. After each suction reading, a Vernier calliper was used to determine the volume of the sample. Fig. 5 gives a photograph of two samples, one near full saturation and one near residual suction, and Fig. 6 shows a photograph of the chambers used to vary water content.

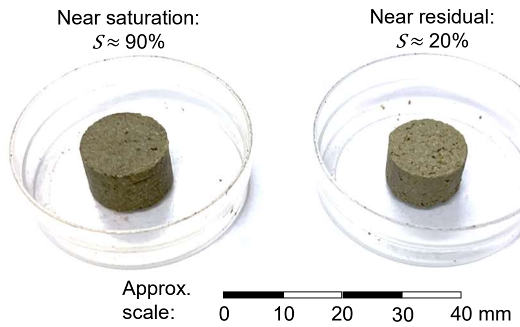

Fig. 5. Photograph of compacted SWRC samples near full saturation and residual conditions.

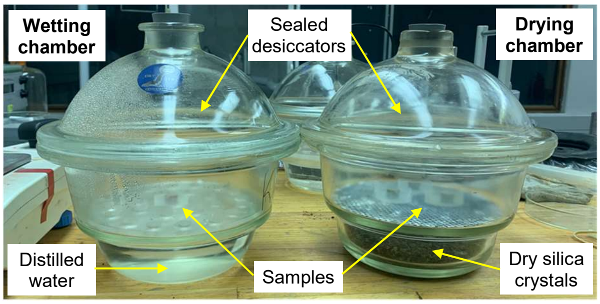

Fig. 6. Photograph of wetting chamber and drying chamber.

5 Results and discussion

Relationships between suction and gravimetric water content (w-SWRC), degree of saturation (S-SWRC) and void ratio (e-SWRC), as well as the relationship between void ratio and gravimetric water content, commonly known as the shrinkage curve (e-w-SC), could all be determined at any given measurement using the following fundamental phase relationships:

$$w = {}^{M}\!/_{M_s} - 1 \quad (1)$$

$$e = {}^{(G_s \cdot \rho_w)}\!/_{(M_s/V)} - 1 \quad (2)$$

$$S \cdot e = w \cdot G_s \quad (3)$$

where: M = Total sample mass
M_s = Mass of solids, determined using Eq. 1, initial mass (M_0) and initial water content (w_0) from a water content sample.
ρ_w = Density of water
V = Total sample volume, determined using a vernier calliper

The initial conditions for the samples, where full saturation was targeted for each, are given in Table 2.

Table 2. Initial conditions for SWRC samples.

Sample:	S3-1	S3-2	S3-3	S3-4
Initial dry density, $\rho_{d,0}$ (kg/m^3)	1496	1476	1406	1225
Initial void ratio, e_0	0.799	0.826	0.915	1.198
Initial grav. water content, w_0 (%)	29.2	30.4	33.0	41.0
Initial degree of saturation, S_0 (%)	98.4	99.1	97.1	92.1

Fig. 7 illustrates how the total suction air-entry value (AEV) was determined by connecting the approximately straight-lined portions of the capillary and funicular regimes in the S-SWRC primary drying curve, per [20]. Air entrapment represents the difference between the initial degree of saturation before drying and final degree of saturation after wetting. The shrinkage limit and minimum void ratio were determined using constructions on the drying shrinkage curve, also illustrated in Fig. 7. The measured primary drying and wetting curves are reported in Fig. 8, with key information summarised in Table 3. Note that dewpoint hygrometer readings less than 1 MPa were subject to scatter, consistent with past findings [21], and that the maximum suction that can be accurately measured by the WP4C is 300 MPa [19].

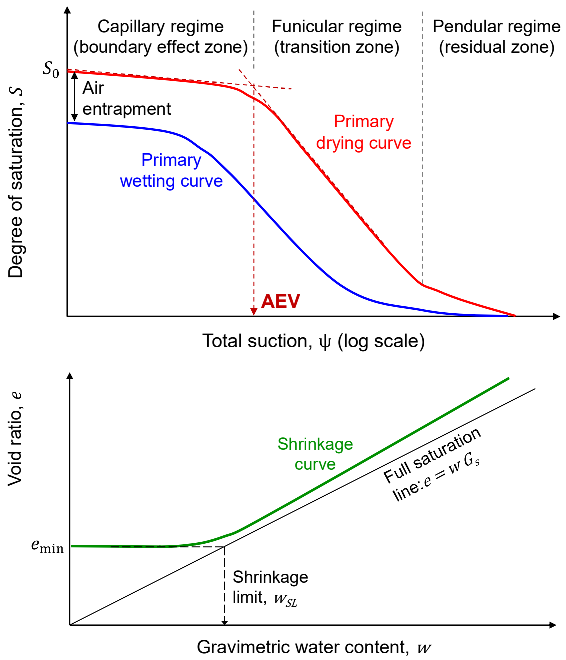

Fig. 7. Constructions used to determine air-entry value (AEV), shrinkage limit and minimum void ratio of each sample.

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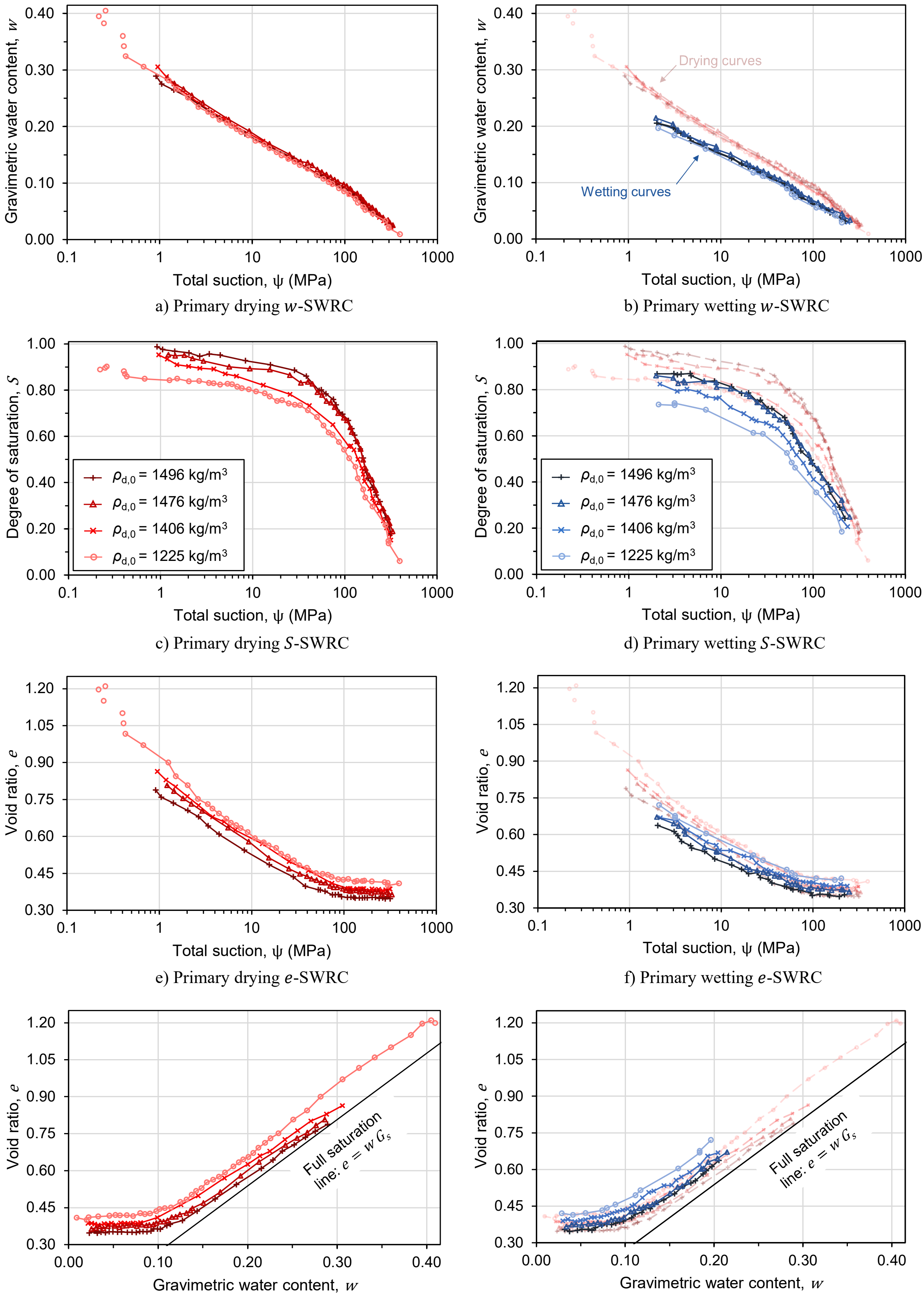

a) Primary drying w-SWRC
b) Primary wetting w-SWRC
c) Primary drying S-SWRC
d) Primary wetting S-SWRC
e) Primary drying e-SWRC
f) Primary wetting e-SWRC
g) Primary drying e-w-SC
h) Primary wetting e-w-SC

Fig. 8. Measured primary soil-water retention and shrinkage curves.

Table 3. Summary of SWRC results.

Sample:	S3-1	S3-2	S3-3	S3-4
Initial dry density, $\rho_{d,0}$ (kg/m^3)	1496	1476	1406	1225
Final dry density, $\rho_{d,max}$ (kg/m^3)	1998	1972	1952	1924
Final void ratio, e_{min}	0.347	0.365	0.379	0.399
Max. volume reduction, $\varepsilon_{v,max}$ (%)	25.0	25.2	28.0	36.3
Shrinkage limit, w_{SL} (%)	12.9	13.6	14.1	14.8
Air-entry value, AEV (MPa)	71	70	70	67
Air entrapment (%)	8.0	8.7	9.5	10.5

The volumetric relationships (i.e. the e-SWRC and e-w-SC) plotted within a narrow band of approximately 0.05 in void ratio with varying initial density. The void ratio at a given suction increased for samples with decreasing initial dry density. The offset between these curves did not change considerably with changes in suction, or across drying and wetting. The greatest variation in measured curves as a function of initial dry density was observed in the S-SWRCs. Greater variation in degree of saturation was visible at lower suctions, whilst the curves converged at large suctions (greater than AEV). The degree of saturation at any given suction increased with increasing initial dry density. The largest difference in degree of saturation between samples was evident within a suction range of 10 to 30 MPa, and was approximately 15% during drying and 18% during wetting. However, the air-entry value was not significantly influenced by initial density. Interestingly, initial dry density had no noteworthy influence on the w-SWRC. These relationships were approximately straight lines in semi-log space. The maximum discrepancy in water content for a given suction was approximately 1% for drying and approximately 2% for wetting.

Each sample showed a hysteretic response between drying and wetting in all four relationships considered. SWRC equations from literature were fitted through the datapoints for wetting and drying, so that hysteresis between wetting and drying curves could be quantified. The Fredlund-Xing [22] equation was used for the S-SWRCs, the M. Fredlund [23] equation for the shrinkage curves, logarithmic best-fit relationships for the w-SWRCs, and the e-SWRCs were determined from the three aforementioned curves. Hysteresis in any parameter was defined as the drying curve value minus the wetting curve value at the same total suction. Hysteresis between wetting and drying over the full measurement range for each test is given in Fig. 9.

Hysteresis in gravimetric water content and void ratio reduced with increasing suction. Hysteresis in degree of saturation peaked at a suction near the air-entry value for each of the samples. Air entrapment (hysteresis at minimum suction) increased with decreasing initial dry density. Conversely, the peak degree of saturation hysteresis increased with increasing initial dry density, ranging between 16% for the least dense sample to 21% for the most dense.

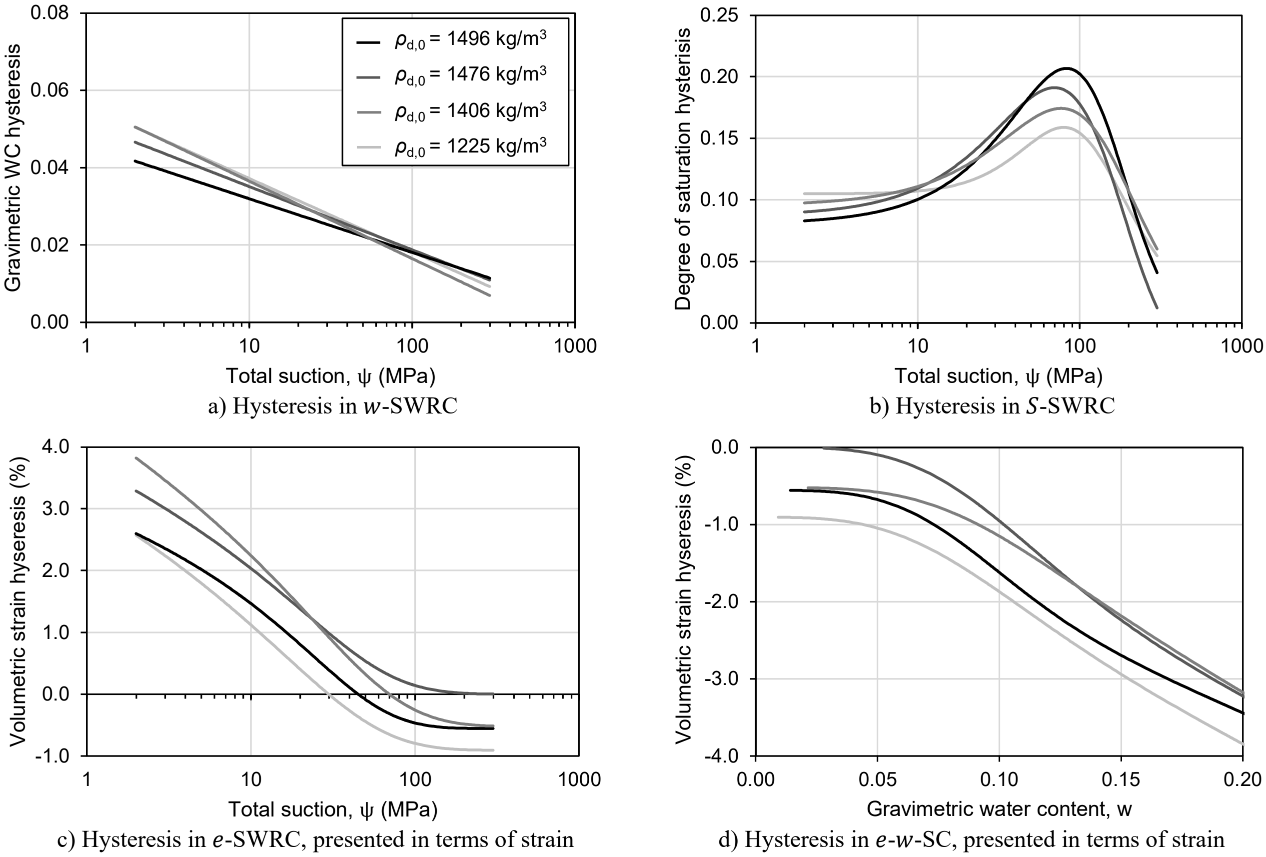

Fig. 9. Hysteresis between fitted primary drying and wetting soil-water retention and shrinkage curves.

Since the shrinkage curves and *e*-SWRCs are essentially only offset vertically, changes in volume modelled using these relationships would not be considerably influenced by the initial dry density to which the sample is prepared. Hysteresis in the wetting and drying volumetric relationships was not significant except near saturation, which suggests that a single primary drying shrinkage curve might be successfully used for modelling volumetric behaviour of this soil. The greatest hysteresis in volumetric strain was 3.8% for any of the tests under any suction state.

However, these results suggest that sample preparation density must be considered for any modelling of unsaturated flow or strength behaviour, where parameters would be calculated from the degree of saturation at a given point. Variations of nearly 20% in degree of saturation near air-entry may result in significant overpredictions of strength. In addition, considerable hysteresis means that specifying a single primary drying *S*-SWRC cannot properly capture the water holding capacity of this soil in wetting at any suction, and especially near air-entry.

6 Conclusions

Gravimetric water content soil-water retention curves in this study were found to be nearly independent of initial dry density. The void ratio curves of samples with varying initial density exhibited a relatively constant offset with varying suction, suggesting that the preparation density of a laboratory SWRC would not significantly influence modelling of volume changes of the expansive clay. Air-entry values of approximately 70 MPa were recorded for all samples. Hysteresis in the *S*-SWRC was significant, which should be considered in modelling of unsaturated strength and flow problems.

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