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TECHNICAL NOTE

Wetting, drying and compression characteristics of compacted clay

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KEYWORDS: clays; compaction; partial saturation; settlement; suction

INTRODUCTION

The placement of fills is often carried out at optimum or close to optimum water content, and they are generally unsaturated (Charles & Watts, 2001; Blanchfield & Anderson, 2000). Regardless of the way the fills are placed, with or without engineering control, it is important to understand their post-placement behaviour in terms of deformation and load-bearing capacity. In temperate climates, initially unsaturated fills often become more saturated owing to infiltration of surface water. There are also instances in which the fills can become drier, for example in prolonged drought. The wetting and drying behaviour of compacted fills under changing environmental conditions has yet to be fully explained. This paper examines such behaviour in the context of elasto-plastic modelling. The work is a natural extension to work carried out previously on compacted clay (Wheeler & Sivakumar, 1995; Sivakumar & Wheeler, 2000).

EXPERIMENTAL WORK

Testing procedures

Commercially available kaolin was used for making samples. The test samples were produced by static compaction at a moisture content of 24·5 ± 0·5% to the same dry density as achieved in the BS test (BSI, 1990: 2·5 kg compaction). A static pressure of 1300 kPa was found to give the desired dry density. After compaction the soil characteristics were: bulk density 1680 ± 20 kg/m^3, initial specific volume 1·95 ± 0·01, degree of saturation 67 ± 2%, and initial suction 800 kPa (measured using pressure plate apparatus). Tests carried out on these samples will be referred to as S1300 in this note. The sample volume change was measured using a 'twin-cell' arrangement similar to that used in the pioneering work of Wheeler (1986). The tests were carried out under controlled suction using the principle of axis translation (Hilf, 1956).

The initial state of the sample after extruding from the compaction mould is indicated by point A in Fig. 1. Two series of tests were performed, as follows.

In *Test Series 1* the samples were equilibrated to suction of 0, 200 and 300 kPa (paths ABE, ABD and ABC in Fig. 1(a)) and a mean net stress ($p - u_a$) of 50 kPa. The samples were then isotropically compressed under constant suction to establish the normal compression line. The mean net stress was ramped at a rate of 15 kPa/day.

In *Test Series 2* the samples were allowed to equilibrate at a suction of 50 kPa (path ABC). Samples were then dried by increasing the suction to 100, 200, 300 and 450 kPa (paths CD, CE, CF and CG in Fig. 1(b)). During this the suction was ramped at a rate of 15 kPa/day at a maintained ($p - u_a$) of 50 kPa. The samples were then isotropically compressed under constant suction to establish the normal compression line. No attempt was made to measure suction at point B. The application of net mean stress of 50 kPa may have reduced the suction in the sample slightly, but for all practical purposes it is assumed to be 800 kPa.

Results from previous work by the first author were used for comparison (Wheeler & Sivakumar, 1995; Sivakumar & Wheeler, 2000). The kaolin samples for these tests were prepared at a moisture content of 24·5%, and statically compacted using pressures of 400 kPa and 800 kPa. The tests will be referred to as S400 and S800 respectively.

RESULTS AND DISCUSSION

The structure of compacted soils plays an important role in their mechanical behaviour (Barden & Sides, 1970; Sridharan *et al.*, 1971; Gens *et al.*, 1996; Romero *et al.*, 2003). Compacted fine silt-clay materials have a bimodal pore size distribution that may be viewed as aggregates of particles in an essentially saturated condition, surrounded by air-filled voids. The size of the aggregates is largely dependent on the sample preparation prior to compaction. The size of aggregates and the compaction pressure both determine the actual pore size distribution. Increase in compactive effort reduces the inter-aggregate voids, but it has no notable influence on the intra-aggregate pore size distribution (Lloret *et al.*, 2003). The data reported here were obtained on statically compacted samples of kaolin prepared using three different compaction pressures: 1300 kPa, 800 kPa and 400 kPa. In all cases, the material for compaction was prepared in a similar manner with an identical initial water content so that the pore size distribution of the raw material was the same for all tests. Mercury intrusion tests were performed to establish the nature of the bimodal pore size distribution. Fig. 2 shows the results obtained on samples compacted to three different compaction efforts. The results show a clear indication of bimodal pore size distribution, where inter-aggregate pore spaces reduce with increasing compactive effort. The influence of compactive effort on the intra-aggregate voids was less significant as the compaction water content was similar for all three compaction pressures.

Wetting

As the initial suction in the samples was significantly higher than the suction values applied subsequently, the samples drew in water during the equalisation process (paths BC, BD or BE in Fig. 1(a) and path BC in Fig. 1(b)). During this process, the reduction in suction in the individual aggregates will be associated with an increase in aggregate sizes. Assuming no significant distortion of the aggregates, an increase in overall voids ratio can be expected (Alonso *et al.*, 1995; Lloret *et al.*, 2003). However, when the

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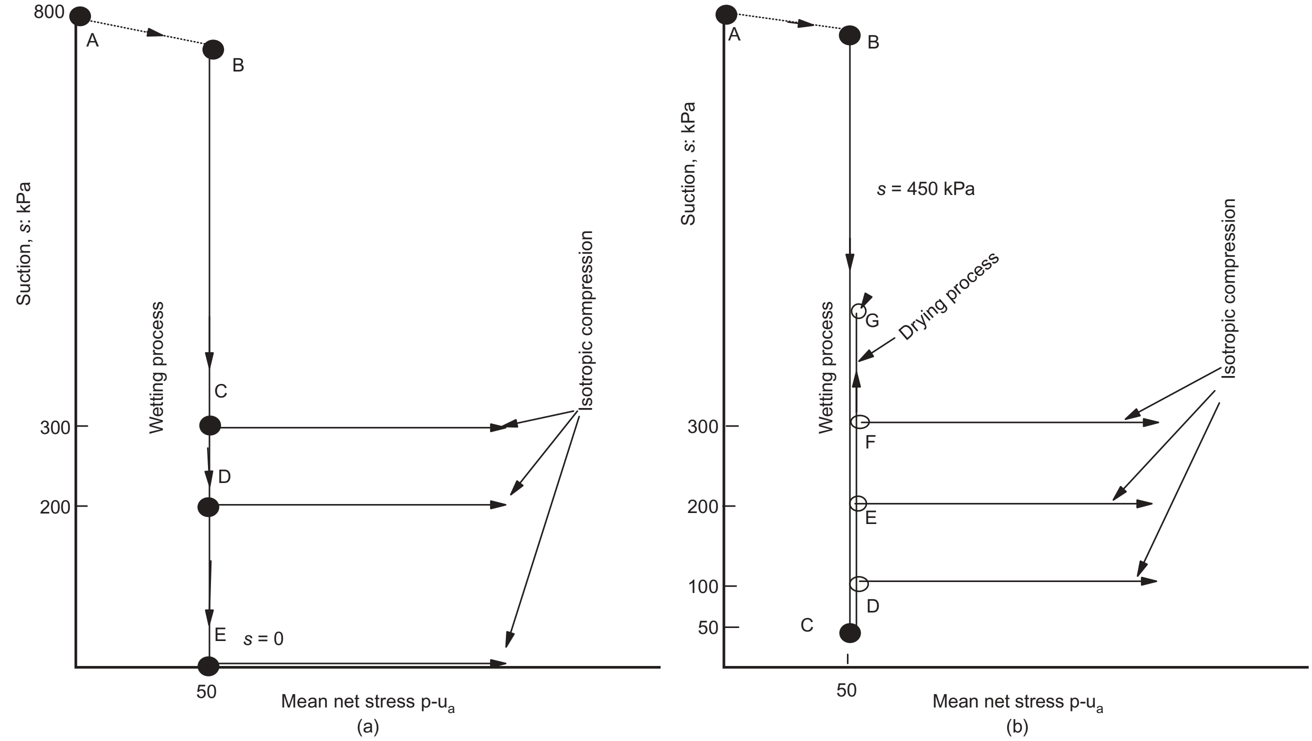

Fig. 1. Testing programme: (a) Test Series 1, wetting and compression; (b) Test Series 2, wetting, drying and compression

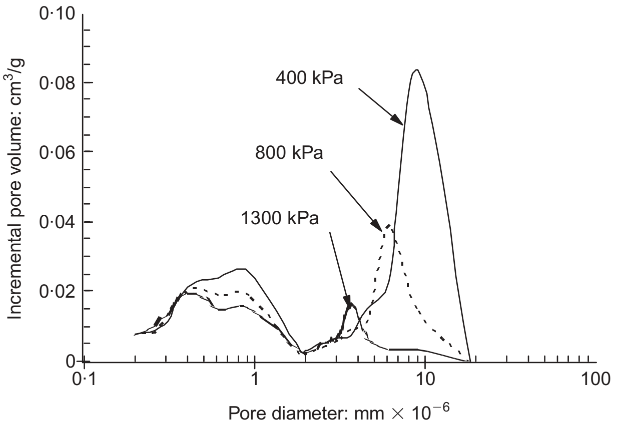

Fig. 2. Pore size distribution of compacted kaolin

suction in the aggregates falls below a critical value, the system of stresses acting on the aggregates may force them to distort and occupy the more open pore spaces, leading to an overall reduction in voids ratio. Water will also be taken up by the menisci at the aggregate contacts, reducing the inter-aggregate stresses and the shear strength at the contacts. This can lead to collapse settlement. The relative influence of these factors determines the response of the compacted clays during the initial wetting.

Figure 3 shows the specific water volume (v_w) after equalisation of the S1300 samples in Test Series 1 and 2 plotted against natural logarithm of a modified suction (shown by square data points and the dashed line). The atmospheric pressure (p_{atm}) of 100 kPa is introduced in the coordinate suction axis as $\ln[(s + p_{atm})/p_{atm}]$ to avoid difficulties of representing $s = 0$ when using a logarithmic scale (Alonso *et al.*, 1990). The initial compaction water content corresponds to a suction of 800 kPa measured using the pressure plate apparatus. Other values of suction are those applied subsequently to the sample when tested in the

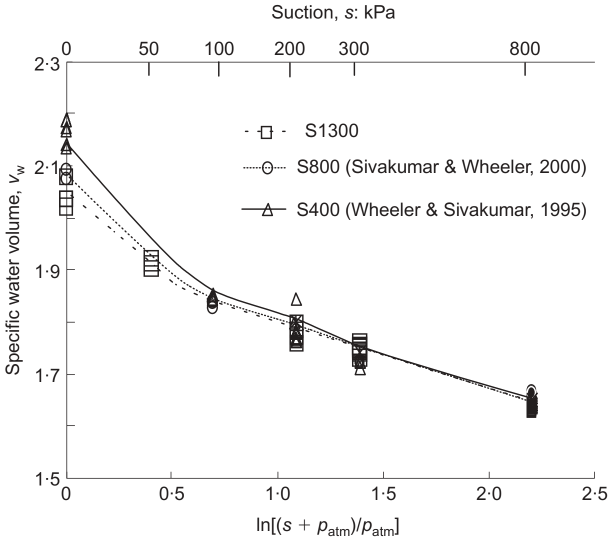

Fig. 3. Variation of specific water volume during wetting process

triaxial cell. The relationship between the specific water volume and the suction can be represented by a simple curve, which appears to be approximately linear (i.e. based on logarithmic suction scale) between the suction value of 800 kPa and approximately 100 kPa, but deviates from this at low suctions.

The data obtained by Sivakumar & Wheeler (2000) and Wheeler & Sivakumar (1995), represented by S800 and S400 respectively, are also included in Fig. 3. Since in each case the samples were compacted at the same moisture content, they all had the same specific water volume at the beginning of the wetting process. Accordingly it may be assumed in the following that the initial suction is approximately 800 kPa in all three series. The data can be best described by simple curves of a similar form for each compactive effort. The results show that the compaction effort (or the initial bulk density) has little influence on the v_w–ln s relationships at large values of suction. This can be attributed to the fact that the initial bulk density has no significant influence on the pore size distribution of intra-aggregate voids. This is consistent with the previous argument that equilibrium entails that the water that flows into the soil is taken up primarily by the individual aggregates.

There will be a significant variation in the inter-aggregate voids depending on the level of compaction pressure (Fig. 2). The effect of this is particularly evident in the v_w–ln s relationship at low values of suction when the void spaces between the aggregates begin to close and fill with water. The samples compacted to 400 kPa have larger inter-aggregate void sizes than the samples compacted to 1300 kPa. Therefore the inter-aggregate pore spaces of samples compacted to 400 kPa will present less resistance to aggregate swelling and distortion, and become more readily flooded with water at relatively larger values of suction than the samples with a smaller inter-aggregate pore size distribution (i.e. samples compacted to 1300 kPa of vertical pressure). In accordance with the foregoing discussion, if (a) the aggregates were saturated when the samples were compacted, and (b) the water that flowed into the samples during the equalisation stage was taken up by the swelling of the individual aggregates, it is possible to extend the arguments concerning water uptake. It may be postulated that water that flowed into the samples through the larger pore spaces during the equalisation stage was drawn into the smaller pores by suction on establishment of equilibrium conditions. The water uptake will have led to swelling of the aggregates. While it would be desirable to compare directly the amount of water entering the samples with the swelling of the aggregates, this is done indirectly. The aggregates may be considered to have remained at constant volume irrespective of the compactive effort if the water content does not change (Fig. 2). However, there may be distortion on the addition of external load, and distortion and volume change on the addition or removal of water. The swelling gradient κ for reconstituted saturated kaolin (where κ is the slope of the unloading line when the specific volume of the sample is plotted against the natural logarithm of $(p - u_w)$ is around 0·03 (Sivakumar *et al.*, 2002). The swelling of the saturated aggregates within unsaturated soils is more complex. Around the aggregates are large air voids with aggregate-to-aggregate contacts maintaining equilibrium. Plotting v_w (a measure of the volume of the saturated regions) against ln$(p - u_w)$ (not shown here), the swelling gradient of the aggregates may be estimated as around 0·10 and is greater than the swelling index for a saturated soil. This implies that the aggregates expand into the larger inter-aggregate voids against low resistance (free swelling) (Fig. 4). As the aggregates expand they interact more as saturation is approached, and the stress level between the expanding regions increases to $(p - u_w)$ throughout the soil. There is thus an increase in confining stress on aggregate expansion, which entails a reduction in swelling gradient on saturation.

The S1300 samples exhibited swelling during the equalisation and no evidence of collapse settlement, as shown in Fig. 5. Comparing Fig. 5 with Fig. 3 (only in the case of samples tested in S1300), the change in v_w is considerably greater than the change in v, consistent with the previous argument of expansion of the saturated aggregates into the larger inter-aggregate voids (Fig. 4). The S400 samples showed swelling when the suction was reduced to 300 kPa, but there then appears to have been a transition, and when the suction was reduced to 100 kPa the samples showed a small amount of collapse. The collapse volume change became significant when the suction was reduced to zero. In the case of the S800 and S1300 samples, swelling occurred at all values of suction considered.

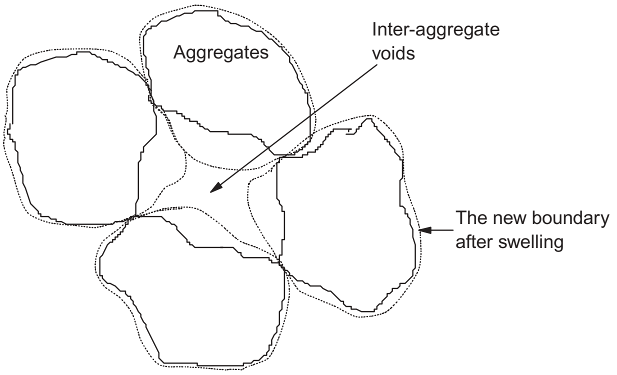

Fig. 4. Swelling of aggregates into the inter-aggregate voids during wetting

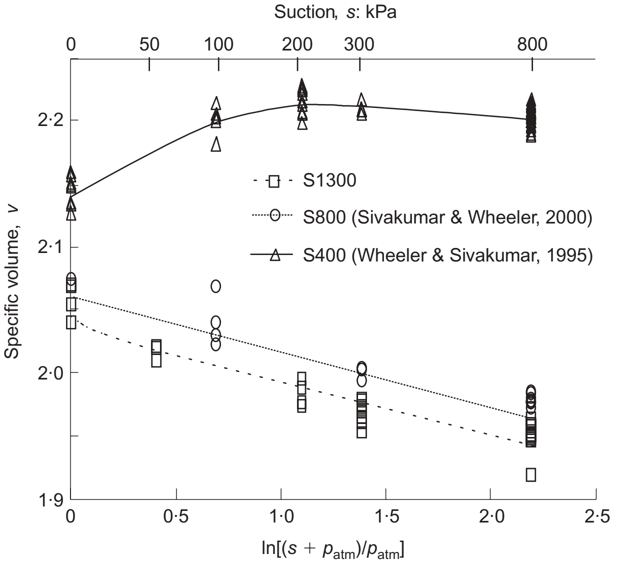

Fig. 5. Variation of specific volume during wetting process

Wetting and drying

In S1300 of Test Series 2 the samples were initially wetted from an initial suction value of 800 kPa and then dried by increasing suction to preselected values. Fig. 6(a) shows the variation of specific water volume v_w against natural logarithm of suction during the drying.

Significant differences in the wetting and drying curves can be seen when the specific water volume is plotted against suction. Similar effects have been documented by a number of researchers (Ray & Morris, 1996; Ng & Pang, 2000; Wheeler *et al.*, 2003), and they can be attributed to hydraulic hysteresis and the expansion and distortion of the saturated aggregates. Wheeler *et al.* (2003) produced a conceptual model to explain the hydraulic hysteresis observed during wetting and drying of fine materials. The experiments of Wheeler *et al.* (2003) imply that voids that are air-filled at a given value of suction during wetting are water-filled at the same suction during drying, irrespective of the pore size distribution. Here this conceptual model should relate to inter-aggregate voids, if intra-aggregate voids were water-filled throughout wetting. Fig. 6(a) therefore suggests that inter-aggregate voids, which have been previously occupied by air during wetting, may have re-

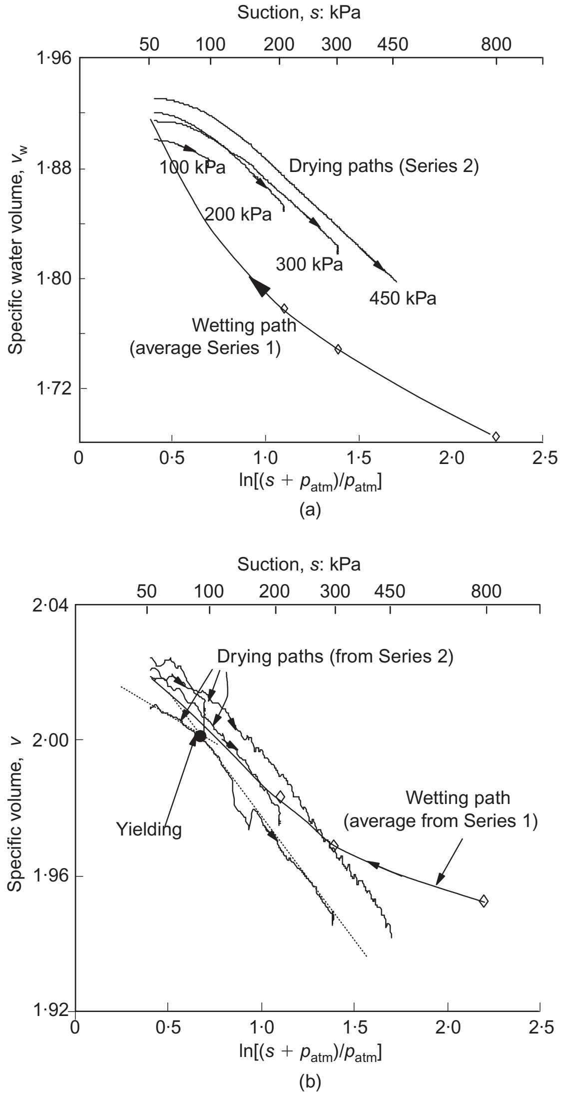

Fig. 6. Specific volume/specific water volume suction characteristic during wetting and drying: (a) specific water volume; (b) specific volume

mained water-filled to suction of at least 450 kPa during drying.

Figure 6b shows the relationship between suction and specific volume during the wetting–drying process. As with specific water volume, the plot during drying is significantly different from that during wetting. The difference is a result of hydraulic hysteresis and aggregate volumetric and distortional changes. The data obtained from the wetting process shown by diamond data points (average from Series 1) are connected by a smooth curve. Subsequently, on drying, the separation from the wetting curve suggests that irreversible volume change commenced (yielding) at suction value of around 200–300 kPa, significantly less than the suction generated by the initial compaction process. Similar observations have been made by Alonso *et al.* (1995) and Sharma (1998) (kaolin–bentonite mixture). The reason for this is believed to lie in the conclusion of Wheeler *et al.* (2003), who demonstrated that the stability of a soil skeleton is not particularly influenced by the suction in the meniscus water, but is determined by the number of soil/meniscus water contacts. When the soil samples were wetted from the initial suction value of 800 kPa to 50 kPa the inter-aggregate pore spaces reduced in size, and a number filled with water. In accordance with Wheeler *et al.* (2003), subsequent drying of the samples by increasing the suction would lead to a greater number of inter-aggregate pore spaces being filled with water (greater degree of saturation) than at an equivalent value of suction on the drying curve and significantly fewer soil/meniscus water contacts. This is consistent with the plots of v_w–ln$s$ in Fig. 6(a). Hence during the drying process the stabilising effect provided by the meniscus at the inter-aggregate contacts is considerably less than for the samples during the wetting process. The sample thus yielded at a lower value of suction than it previously experienced following sample preparation.

Isotropic compression

Figure 7(a) shows the relationship between v and ln($p - u_a$) relationship for Test Series 1 samples subjected to isotropic compression after wetting to pre-selected values of suction. One of the problems in soils is that the yielding does not take place abruptly, that is, at a given pressure. It normally takes place over a range of pressures, leading to a smooth transition from elastic behaviour to elasto-plastic behaviour. This makes the assessment of yielding from laboratory tests more difficult, and the estimated yield pressures from Fig. 7(a) are 90 kPa, 165 kPa and 210 kPa for suction values of 0 kPa, 200 kPa and 300 kPa respectively. The yield stresses were estimated using Casagrande's graphical construction, and they are marked by closed circular data points. The relevant suction and mean net stress at the point of yielding are shown in Fig. 8, which represents the form of the LC yield locus. The shape of this curve agrees with the theoretical considerations and the experimental evidence of others (Alonso *et al.*, 1990; Wheeler & Sivakumar, 1995; Cui *et al.*, 1996).

Figure 7(b) shows the compression lines for samples initially wetted by reducing suction to 50 kPa and then dried by increasing the suction to 100 kPa, 200 kPa or 300 kPa (Test Series 2) with estimated yield pressures 55 kPa, 80 kPa and 130 kPa respectively. The yield pressures are marked in Fig. 7(b) by open circular points. The relevant suction and mean net stress at the point of yielding are shown in Fig. 8, which represents the form of the LC yield locus in the s:($p - u_a$) plane. The yield pressures in this case are significantly less than the yield pressures estimated from the isotropic compression tests carried out on the samples wetted to preselected values of suction. This can be explained using the framework proposed by Wheeler *et al.* (2003). Consider two samples: sample A initially wetted to 200 kPa of suction, and sample B initially wetted to 50 kPa of suction and subsequently dried to 200 kPa of suction. In the tests undertaken, the wetting and drying processes were performed at ($p - u_a$) of 50 kPa. Samples A and B thus have identical stress state variables ($p - u_a$) and ($u_a - u_w$), but in accordance with previous arguments sample B has a large number of inter-aggregate voids filled with water (or alternatively fewer soil/meniscus water contacts). Therefore sample B is less stable than sample A. Sample B is thus more susceptible to yield than sample A if ($p - u_a$) is increased at constant suction. This is consistent with the plots in Fig. 8.

CONCLUSIONS

This note has reported some experimental data obtained on samples of compacted kaolin when taken through wetting, drying and isotropic compression loading. The results have shown that the relationship between the specific water volume and the suction was unaffected by compaction effort at suction values higher than 100 kPa. This implies that the water that flowed into the samples during the wetting process

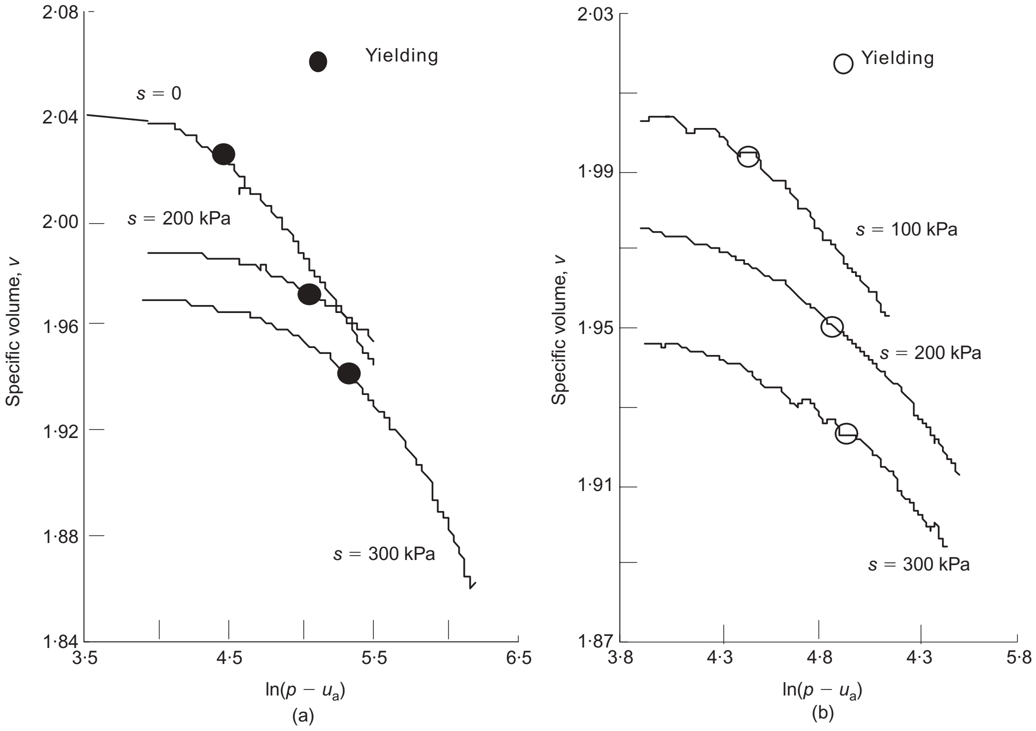

Fig. 7 Volume–pressure characteristics of samples during isotropic compression: (a) compression following wetting (Test Series 1): (b) compression following wetting and drying (Test Series 2)

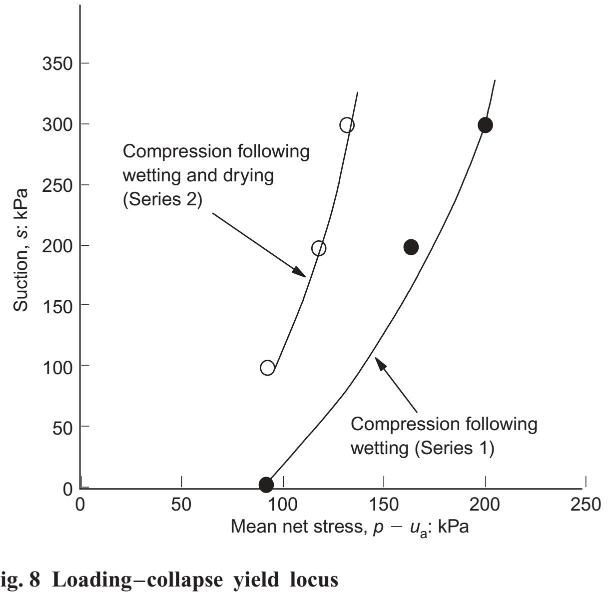

Fig. 8 Loading–collapse yield locus

was taken up largely by individual aggregates within the bimodal structure. Observations of volume changes during drying and the corresponding increase in suction were interpreted as consistent with hydraulic hysteresis and the swelling and distortion of the saturated aggregates. The samples during the drying process had a higher degree of saturation at a given value of suction than the samples wetted directly to the same value of suction. This increase in the degree of saturation led to a reduction in the stabilising effects between inter-aggregate contacts, leading to yielding at smaller values of suction during the drying process compared with the maximum suction on sample preparation. The hydraulic hysteresis also affected the observed yielding of the samples during loading by increasing $p - u_a$.

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NOTATION

LC	loading collapse yield locus
p	mean stress
p_{atm}	atmospheric pressure
s	suction
u_a	pore air pressure
u_w	pore water pressure
v	specific volume
v_w	specific water volume
κ	swelling gradient for reconstituted saturation kaolin

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