Drying induced effects on the residual strength of remoulded clays

V. Merchán, J. Vaunat & E. Romero
Universitat Politècnica de Catalunya, Barcelona, Spain

Keywords: Aggregation, high suction, residual strength, remoulded clay

ABSTRACT: Experimental tests on residual shear strength of clays using “high suction control system” have shown that the friction angle significantly increases at high suction , and that such an increase is more significant as the plasticity index increases (Vaunat J. *et al*. 2006; Meca 2007; Vaunat J. *et al.* 2007). These results are not in agreement with the classical results on saturated soils where the residual friction angle reduces as plasticity index increases (Bishop 1971; Lupini J.F. *et al*. 1981; Skempton 1985). This paper intends to explain these results by taking into consideration the microstructure of the tested materials. In particular, direct observations after tests with Environmental Scanning Electron Micrographs (ESEM) and Microstructure Intrusion Porosimetry (MIP) techniques were used. The analysis shows that samples undergo microstructural changes due to drying: micro-cracking, stiffening and developing of aggregate arrangements and changes in microporosity are the main observed features. These microstructural changes seem to develop a stiffer material which indeed behaves in a “granular” way in terms of strength.

1 INTRODUCTION

The study of residual shear strength at high suctions had been developed recently at Universitat Politècnica de Catalunya (UPC) with a first adaptation of the classic Bromhead ring shear apparatus to high suction control through the vapour transfer technique (Vaunat *et al*. 2006). At that time a low plastic material was tested (Barcelona clayey silt) and an increase of ~5° in residual friction angle at high total suction (S~ 75MPa) was observed. Then, Boom clay (medium plastic) and FEBEX bentonite (high plastic) materials were tested resulting in a huge increase (> 15º) of residual friction angle upon the application of high suction (Vaunat *et al*. 2007; Merchán *et al*. 2008). Those results suggested that some kind of stiffening was induced to the samples during the drying process; samples were initially prepared at water content between liquid and plastic limit and then dried by vapour transfer using saline solutions to apply a given relative humidity over the sample.

In this paper these previous experimental results are discussed in the light of the microstructural changes occurred in the soil mainly during drying. To this end, results on MIP and ESEM tests are presented and discussed.

2 ADAPTED BROMHEAD RING SHEAR APPARATUS

The Bromhead ring shear apparatus is one of the simplest apparatus to measure residual strength of saturated clays. It consists of an annular ring which contains the sample (dimensions of 100mm and 70mm of external and internal diameter respectively and 5mm in height) as shown in Figure 1. Shearing is applied by a torque system on the upper surface of the sample. Some of the advantages of this device are: the attainment of large displacements of shearing and the simple operation of the system. On the other hand, the main drawback is the uncertainty about the stress state of the sample and the loss of sample material in the upper side due to rotation effects during shearing. This occurred frequently on plastic soft materials under saturated conditions.

In order to study the effects of high suction on the residual shear strength of clayey materials, the Bromhead ring shear apparatus was adapted to control the relative humidity of the environment around the sample. The adaptation consists in the design and construction of a glass cap (Figure 2) with special inlets and outlets in order to apply and maintain high suctions by vapour transfer technique. Figure 3 shows a picture of the adapted device; one of the inlets allows the placement of the hygrometer (HMT 100 from Vaisala, +/- 1.7%RH at 0-90%RH and +/-2.5% at 90-100%RH), used to measure relative humidity and temperature of the nearby sample environment. A second inlet allows the inflow of vapour from the vessel containing the saline solution and the outlet is used to close the system by returning the vapour to the air pump.

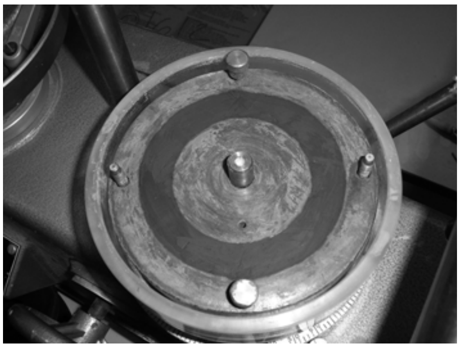


Figure 1. Annular sample installed inside the Bromhead ring shear apparatus.

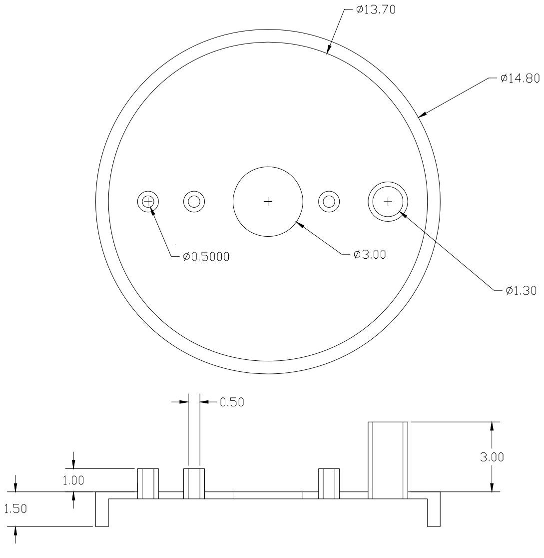


Figure 2. Glass cap designed to isolate the annular sample from the environment (Vaunat *et al*., 2007).

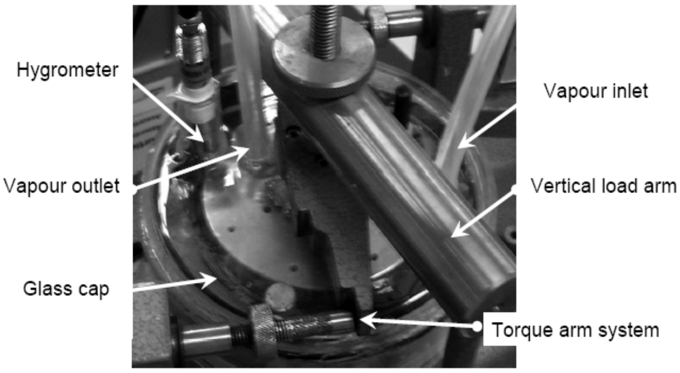


Figure 3. Bromhead adapted system with vapour transfer technique.

3 TEST PROTOCOLS AND MATERIALS

Figure 4 shows the general scheme of the system. It can be observed that the relative humidity imposed to the air of the vessel containing the saline solution is forced to reach the sample through an air pump. Then, the environment surrounding the sample and the sample itself will equilibrate with the suction applied by the saline solution. Real time data from the hygrometer and from the vertical displacement of the sample is stored on a computer through an USB device (National Instruments NI9001). The general procedure to test a single sample at a given relative humidity takes about 1 month and involves the following steps:

- Preparation of a remoulded sample between plastic and liquid limit. It is possible that the initial water content has an influence on the final residual shear strength after suction application; however this point is still a matter of current research. In saturated tests this point does not have any consequence (Garga 1970; La Gatta 1970; Bishop 1971).
- Consolidation of the sample under a given normal stress.
- Suction application by the vapour transfer technique. At this point, sample volumetric change is measured through a linear variable displacement transformer (LVDT) in terms of vertical displacement; also relative humidity (RH) and temperature through the hygrometer are measured in real time. Sample is assumed to have reached equilibrium when the volumetric change is less than 0.5% per day.
- Shearing through the application of rotation at slow constant rate (0.012°/min) in order to keep ‘drained’ conditions.

Figure 5 presents an example of the data acquisition system during the consolidation, drying and early stage of shearing stages for a Boom clay sample. As observed in the figure, the consolidation stage takes about 24h, then during drying the sample presents important shrinkage (vertical displacement evolution) during 14 days, the time necessary to reach equilibrium. Finally, during the early stage of shearing, the sample presents some dilation (indeed this dilation is coupled with pick strength at the same time) which tends to disappear as shearing progresses.

Three materials have been tested in order to cover a wide range of plasticity index; Barcelona clayey silt (low plasticity), Boom clay (medium plasticity) and FEBEX bentonite (high plasticity).Table 1 presents their main index properties.

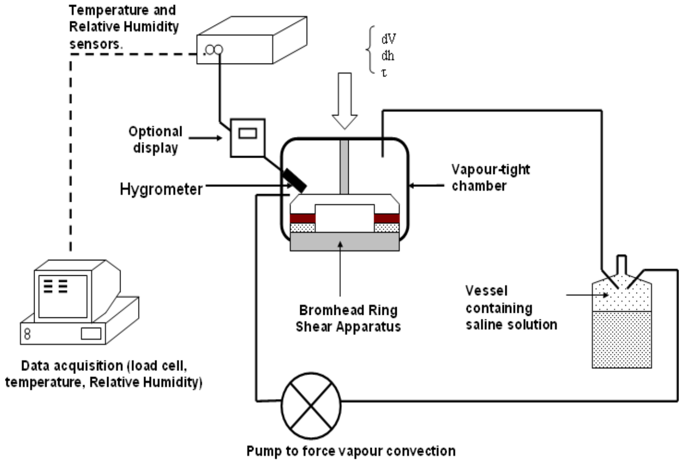


Figure 4. General scheme of the adapted Bromhead ring shear apparatus.

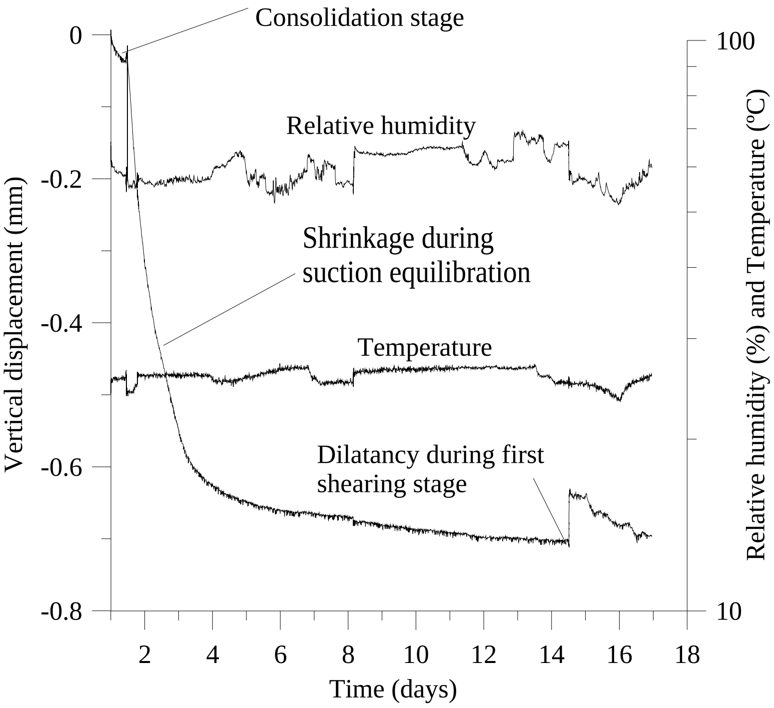


Figure. 5 Data acquisition during consolidation, drying and early stage of shearing for Boom clay sample.

Table 1. Average index properties of the tested materials.

Property	BCN clayey silt	Boom clay	FEBEX bentonite
Liquid limit (%)	30	55	102
Plastic limit (%)	16	28	53
Density of solids ρ_s (Mg/m^3)	2.66	2.7	2.7
Clay fraction < 2µm (%)	15	40	68

4 TEST RESULTS

Following this protocol a series of ring shear tests at different vertical stress and suctions were performed on these materials. Figure 6 compares two envelops of residual strength for Barcelona clayey silt at two different total suctions. In saturated conditions, this material shows a residual friction angle of ϕ_r~ 20°. On the other hand, the envelope at S~75 MPa gives a residual friction angle of ϕ_r~ 24°. In the case of Boom clay, the saturated envelope shows a residual friction angle of ϕ_r~ 13° and the envelope at S~140 MPa results in a residual friction angle of ϕ_r~ 30° (Figure 7). Similar results were obtained for FEBEX bentonite, where an important increase in residual shear strength was detected after strong drying of the samples (Figure 8). The envelope under saturated conditions showed a ϕ_r~ 8° and at S~21MPa the residual friction angle increases up to ϕ_r~ 20°. The last envelope of these tests at S~70MPa gives a residual friction angle of ϕ_r~ 29°. The results obtained for the plastic materials led to the hypothesis of aggregation of the microstructure of the clays during drying stage. This hypothesis is discussed in the next section in the light of the microstructural observations.

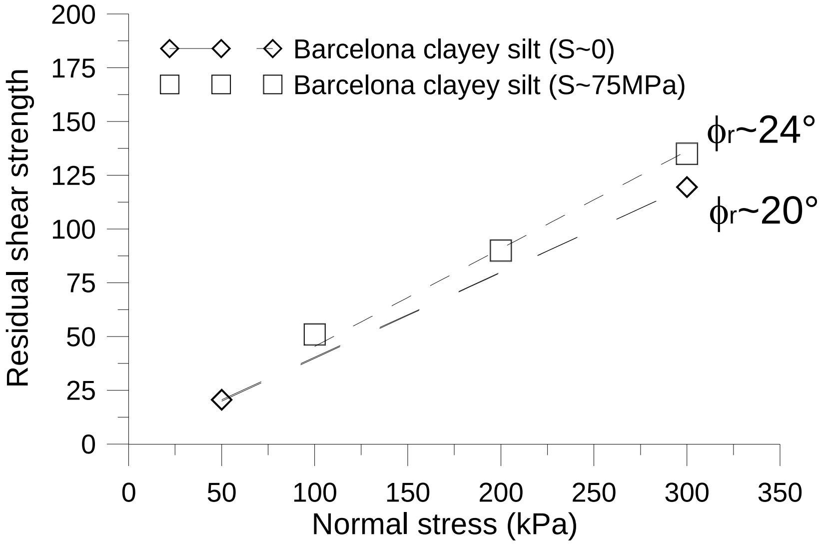


Figure. 6. Residual shear strength envelopes for Barcelona clayey silt (low plasticity).

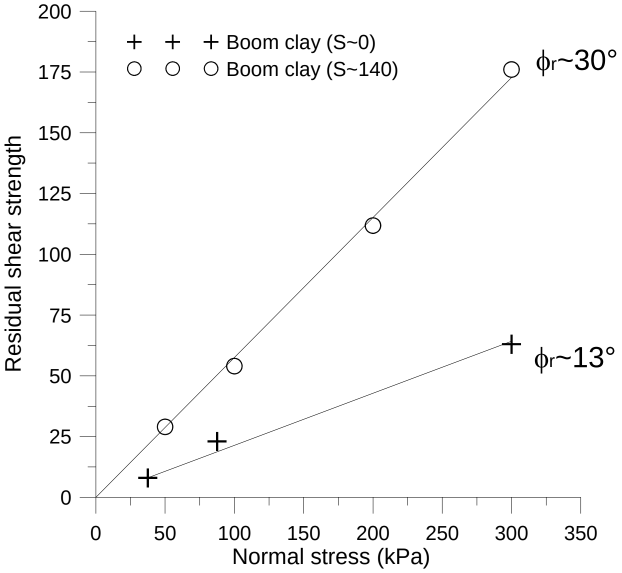


Figure 7. Residual shear strength envelopes for Boom clay (medium plasticity).

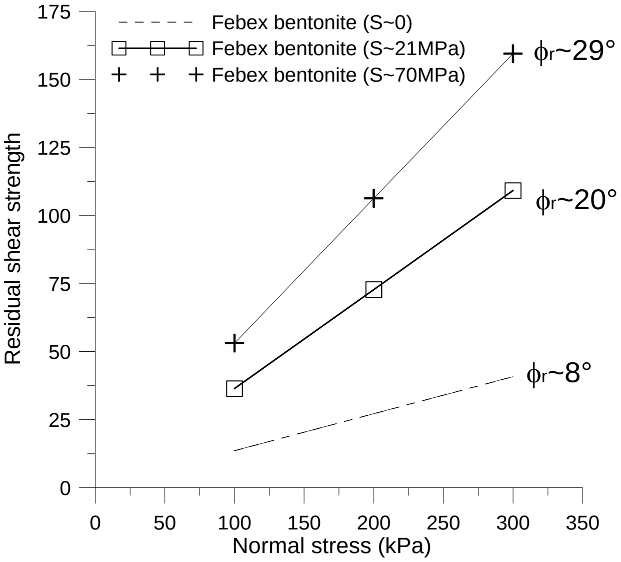


Figure 8. Residual shear strength envelopes for FEBEX Bentonite (high plasticity).

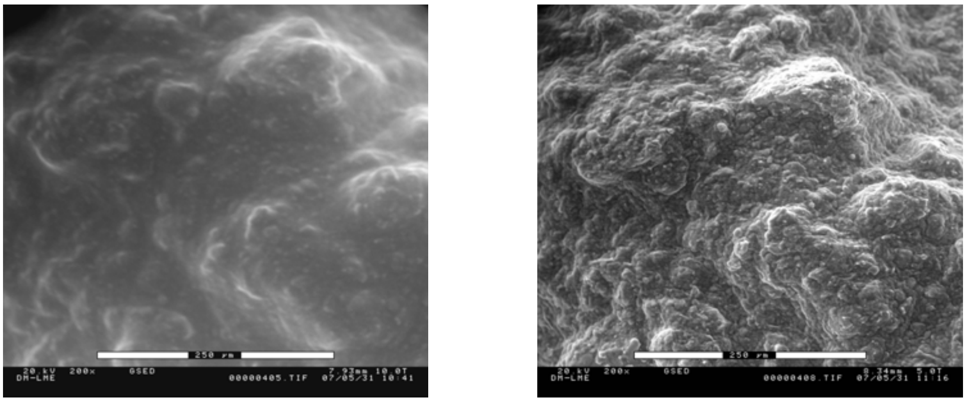
5 MICROSTRUCTURAL OBSERVATIONS

A series of ESEM and MIP tests were carried out in order to understand how the drying process affected the microstructure of the soil.

5.1 *ESEM Tests*

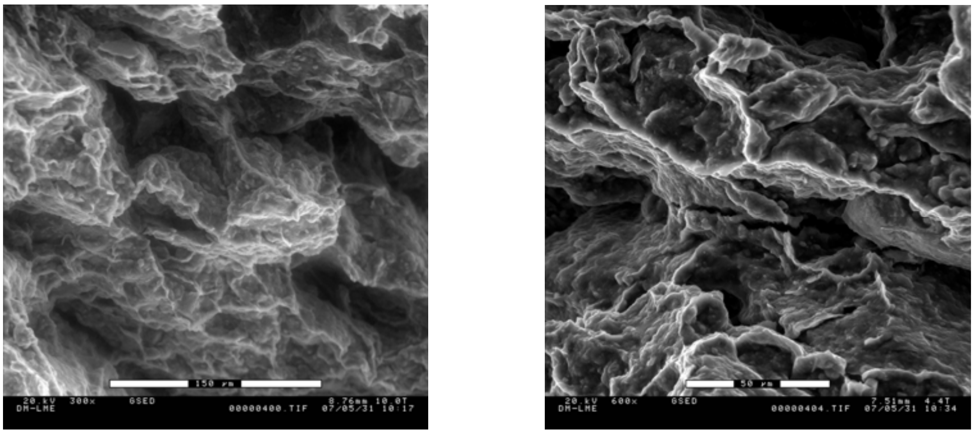
A series of photomicrographs were taken on ESEM device in order to have a qualitative idea of the microstructure of the materials (a) at initial condition and after drying process inside the ESEM device, (b) after consolidation and drying stages, and finally (c) after consolidation, drying and shearing stages. In this paper, only the micrographs of Boom clay will be shown.

Figure 9a shows a photomicrograph of Boom clay sample prepared at liquid limit. A more or less homogenous arrangement with no micro-voids can be seen. Then, this sample was dried in the ESEM chamber changing the vapour pressure and temperature conditions. After equalization, a photomicrograph was taken (Figure 9b). When comparing these two micrographs, it can be observed that shrinkage occurred during drying leading to a “stiffer” microstructure. In both photomicrographs, no inter-aggregate porosity is observed. Figure 10a shows a sample prepared at plastic limit. A quiet different arrangement is observed. In this case, the presence of an aggregated structure with inter-aggregate porosity is quiet clear. This arrangement undergoes micro-cracking and also shrinkage during drying as it can be seen on Figure 10b. Figure 11 shows a photomicrograph for a sample initially prepared at plastic limit, then consolidated to 100kPa and then dried up to S~70MPa. Again after drying, an aggregated arrangement with few macro-voids is detected. Finally, Figure 12 shows a sample that underwent consolidation, drying and shearing stages. A similar arrangement to that observed in Figure 11 is detected.



(a) (b)

Figure 9 Sample of Boom clay prepared at liquid limit: (a) Initial state (b) After drying on ESEM equipment (RH~10%). (bar length 250μm)



(a) (b)

Figure 10 Sample of Boom clay prepared at plastic limit: (a) Initial state (b) After drying on ESEM equipment (RH~10%) (bar length 150 μm and 50 μm, respectively)

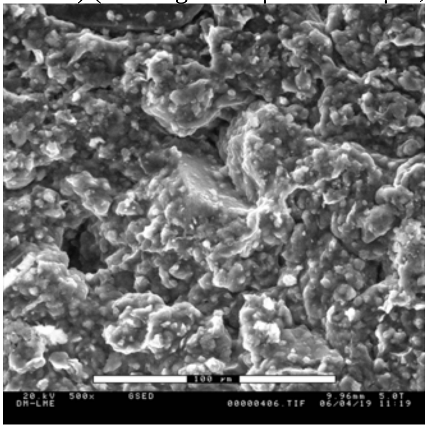


Figure 11 Samples of Boom clay prepared at plastic limit after consolidation and drying stages (bar length 100μm).

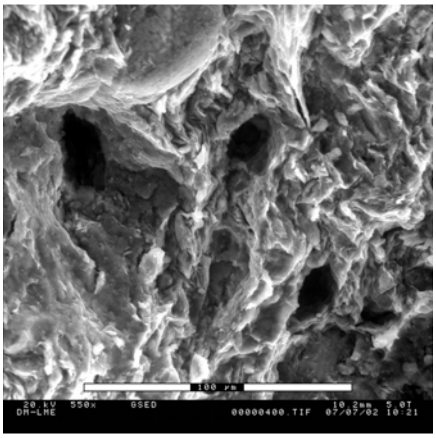


Figure 12 Sample of Boom clay prepared at plastic limit after the test (bar length 100µm).

5.2 *MIP tests*

Quantitative analysis of pore size distribution was carried out by MIP tests on remoulded samples of FEBEX bentonite and Boom clay prepared at plastic limit. Figure 13 shows the pore size distribution curve for two bentonite samples at initial (saturated) and final states (after consolidation, drying and shearing stages). An important difference between the two extreme states is clearly detected. The initial state is characterized by a mono-modal distribution with main pore size diameter of 1µm. The distribution curve corresponding to the final state appears to show a bimodal curve. The pore size diameter detected at 0.020 µm corresponds to the intra-aggregate porosity inside aggregates, while the no so clearly developed mode at values higher than 10µm can be assimilated to the voids between aggregates. Nevertheless, it is important to emphasize that the curve for the aggregated material does not display so clearly the presence of macroporosity as it is usually observed in compacted clayey materials (Lloret et al. 2003; Delage 2007). A similar behaviour was observed for the remoulded samples of Boom clay (Figure 14). In this case, the distribution curve for a sample prepared at plastic limit and then consolidated to 100kPa shows a dominant pore size of 0.3µm. Again, the dried material shows a shifted microporosity with a peak at 0.04µm as a consequence of shrinkage, developing some macroporosity at >10µm that is no so clearly detected within the range of the MIP test.

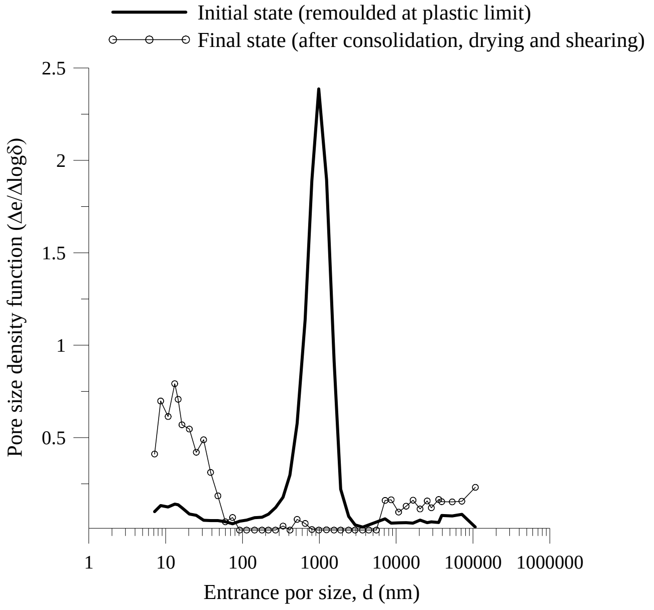


Figure 13 Pore size distributions of two samples of FEBEX bentonite; at its plastic limit and after consolidation, drying and shearing stages.

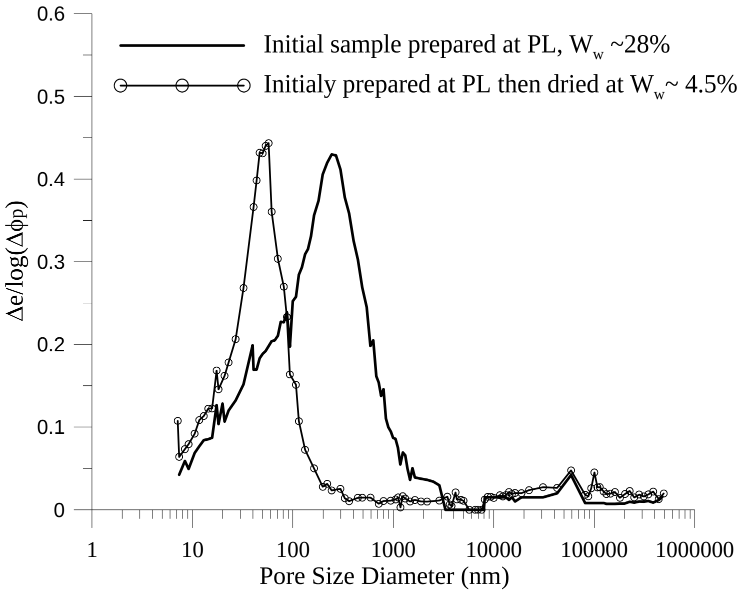


Figure 14 Pore size distributions of two samples of Boom clay, one prepared at plastic limit and then consolidated and another sample at the same initial conditions but then dried and sheared.

6 CONCLUDING REMARKS

In this work some aspects related to the residual shear strength of unsaturated materials and its relationship with drying and aggregation of the microstructure have been outlined. The main conclusions are drawn below:

- A simple adaptation of the Bromhead ring shear apparatus was made in order to allow the control of the relative humidity of the environment surrounding the sample during shearing.
- Tests results indicate that high suction influences the value of residual friction angle obtained for the three materials tested. However, this effect is more appreciable in the case of more plastic materials (i.e., Boom clay and FEBEX bentonite)
- High suction application causes strong shrinkage of the samples, which increases as plasticity index increases.
- Qualitative interpretation of ESEM tests suggests that some aggregated structure is initially formed during the preparation of the sample at their plastic limits. During drying the aggregated structure becomes more evident, developing a stiffer microstructure due to shrinkage. In the case of samples initially prepared at liquid limit, a more or less homogenous arrangement is formed at saturated conditions. After drying, shrinkage is detected with stiffening of soil skeleton but without the formation of aggregations.
- Quantitative analysis by MIP tests on samples prepared at plastic limit clearly shows the evolution of microstructure from the initial saturated state (with dominant mono-modal distribution) to the dried state (clearly developed microstructure with some incipient macroporosity).
- It appears that the increase in residual strength is due at least partially to the strong aggregated arrangement developed on drying.

ACKNOWLEDGMENTS

Mr. Merchán wishes to thank Alβan Program, the EU program of high level scholarships for Latin America, scholarship N° E05D052296CO. The support of the European Commission through the Research and Training Network MUSE (Mechanics of Unsaturated Soils for Engineering) is gratefully acknowledged.

REFERENCES

Bishop, A. W. (1971). *Shear strength parameters for undisturbed and remoulded soil specimens*. Proceeding of the Roscoe Memorial Symposium, Cambridge, Foulis.

Delage, P. (2007). *Microstructural features in the behaviour of engineered barriers for nuclear waste disposal*. In proceedings of the 2nd International Conference of Unsaturated Soil Mechanics, Weimar, T. Schanz (Ed.). Experimental Unsaturated Soil Mechanics 112. Springer, Berlin. Germany. Springer, Berlin, Vol. 1: 11 - 32.

Garga, V. K. (1970). *Residual shear strength under large strains and the effect of sample size on the consolidation of fissured clay*. PhD Thesis, University of London, United Kingdom.

La Gatta, D. P. (1970). *Residual strength of clays and clay shales by rotation shear tests*. Harvard Soil Mechanics Series. Cambridge, Massachusetts, Harvard University.

Lloret, A., Villar M.V., Sanchez M., Gens A., Pintado X. and Alonso E.E. (2003). *Mechanical behaviour of heavily compacted bentonite under high suction changes.* Géotechnique **53**(1): 27-40.

Lupini J.F., Skinner A.E. and Vaughan. P.R. (1981). *The drained residual strenght of cohesive soils.* Géotechnique **31**(2): 181-213.

Meca, T. (2007). *The influence of suction on the residual strength of clays*. Dpto de Ing. del Terreno Cartografica y Geofisica. Tesina de grado, Universitat Politècnica de Catalunya, Barcelona, Spain.

Merchán, V., Vaunat J. and Romero E. (2008). *Experimental study of the influence of suction on the residual friction angle of clays.* In proceedings of the 1st European Conference on Unsaturated soils, Durham, UK. D.G. Toll, C.E. Augarde, D. Gallipoli & S.J. Wheeler (Eds.). Unsaturated Soils, Advances in Geo-Engineering. CRC Press Taylor and Francis Group, London: 423 - 428.

Skempton, A. W. (1985). *Residual strength of clays in landslides, folded strata ad the laboratory.* Géotechnique **35**(1): 3-18.

Vaunat J., Amador C., Romero E. and Djéran Maigre D. (2006). *Residual strength of low plasticity clay at high suctions.* In Proceedings of the 4th International Conference on Unsaturated Soils, Carefree, Arizona, USA. G.A. Miller, C.E. Zapata, S.L. Houston & D.G. Fredlund (Eds). Unsaturated soils, Geotechnical Special Publication Nº 147. ASCE, Reston, Virginia. Vol. 1: 1279-1289.

Vaunat J., Merchán V.E., Romero E. and Pineda J. (2007). *Residual strength of clays at high suctions*. In proceedings of the 2nd International Conference on Mechanics of Unsaturated Soils, Weimar, Germany. T. Schanz (Ed.). Theoretical and Numerical Unsaturated Soil Mechanics 113. Springer, Berlin. Vol. 2: 151-162.