On the swelling behavior of shallow Opalinus Clay shale

E. Crisci[1], A. Ferrari[1], S. Giger[2], L. Laloui[1]
[1]*Laboratory for Soil Mechanics, Swiss Federal Institute of Technology, EPFL, Lausanne Switzerland*
[2] *National Cooperative for the Disposal of Radioactive Waste, NAGRA, Wettingen, Switzerland*

ABSTRACT: The Opalinus Clay shale is the selected geological formation for the construction of a deep geological repository in Switzerland. The geomaterial will experience cyclic drying and wetting paths during different stages of the repository life time. The shale, characterized by transversely isotropic behaviour, has the capacity to swell/shrink upon suction variation. The impact of suction variation on the shale behavior is therefore of interest. This paper presents the results on a shallow sourced sample, subjected to a complete hydric cycle in a wide range of applied suction (from ≈0 to 300 MPa). The results highlight the anisotropy in the shale strains and its evolution during the cycle, while slight irreversible strains cumulate.

1 INTRODUCTION

Opalinus Clay is a Jurassic clay shale that has been chosen as host formation for the construction of a high-level radioactive waste repository in Switzerland. One of the key features of the formation is its capacity to swell upon saturation, and therefore to self-seal cracks and fissures that can potentially form during the repository construction. In this context, the volumetric behaviour of the formation upon suction variation is of particular interest. In fact, during the repository construction the formation will be subjected to phases of excavation, ventilation, waste emplacement and backfilling, exposing the shale to drying (during tunnel excavation and ventilation) and subsequent re-saturation due to water movement from the far field to the tunnel. The induced deformation needs, therefore, to be estimated. The suction variation is known to cause a volumetric response of the shale (Ferrari et al., 2014). This response is markedly anisotropic because of its peculiar layered structure (Minardi et al., 2016).

In addition, it is well-known that clayey soils can experience an accumulation of deformation over suction cycles either in swelling or in shrinkage (e.g.: Airò Farulla et al., 2010; Alonso et al., 2005; Sharma and Wheeler, 2000).

This work gives an insight on the results of a cyclic hydraulic loading on a Opalinus Clay sample sourced from very shallow depth (Lausen borehole in northern Switzerland). The shale is subjected to a wetting-drying-wetting sequence over a wide range of total suction applied. An advanced experimental technique is adopted, allowing to assess the anisotropic volumetric strains with suction applied. A focus on the accumulation of irreversible deformation during the cycle, and on the anisotropic features, is provided.

2 MATERIALS AND METHODS

2.1 *Material properties*

Opalinus Clay shale is a highly compacted and partially cemented formation, deposited 174 million years ago. It is composed mainly of sheet silicates, quartz and carbonates in variable proportions (e.g.: clay content varying approximately between 35% and 80%), due to the depositional environment at the time of sedimentation. The formation is found on a wide area comprising the northern part of Switzerland, and has been widely studied at the Mont Terri Underground Rock Laboratory (Bossart and Thury, 2008), where the formation is found at roughly 300 m depth. In the eastern part of the country the formation can be found, instead, at shallower (few tens of meters) or deeper depth (in excess of 1 km). The results presented hereafter were obtained on samples sourced at shallow depth, at about 18 m. The geotechnical characterization of the material is reported in Table 1.

Mineralogical analysis of the selected sample was performed, and the results show a relevant clay percentage, compared to the known range of variation, in line with the composition found from other Opalinus clay sites (e.g.: shaly facies of the formation at the Mont Terri URL): 63.3% clay minerals, 21.0% quartz, 7.6% calcite, 8.1% other minerals.

Table 1 Geotechnical characterization of Opalinus Clay core from the shallow borehole.

Index property	
Porosity (%)	21
Bulk density (g/cm^3)	2.39
Solid density (g/cm^3)	2.74
Water content as-received (wt.%)	10.2
Degree of saturation of the core (%)	100
Plastic limit (%)	24
Liquid limit (%)	36
Plasticity index (%)	12

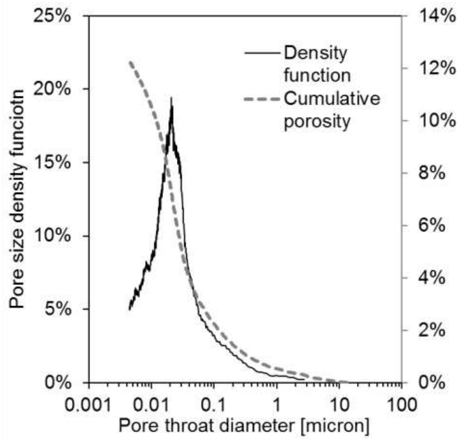

Figure 1 Pore size distribution of Opalinus Clay from 18 m depth, analysed through mercury intrusion porosimetry technique.

Pore size distribution was investigated through mercury intrusion porosimetry (MIP) technique (Figure 1), finding a dominant pore size diameter of ≈20 nm. The total intruded porosity (12%) is considerably below the total porosity found in the characterization. The difference can be attributed to the not intruded pores, below 4 nm in diameter, and to the not connected pores.

2.2 *Experimental technique*

The deformation evolution with total applied suction was investigated adopting an advanced testing methodology combining total suction control with an accurate measurement of the deformations in two orthogonal directions (Minardi et al., 2016).

Wetting and drying steps were applied through the use of the vapor equilibrium technique. The technique consists in controlling the relative humidity inside a closed desiccator through the vapor in equilibrium with various water-based solutions. The relative humidity can be converted to total suction (Ψ) through the psychrometric law (Fredlund and Rahardjo, 1993). Saturated saline solutions are used to impose different total suction values. The used salts are: Lithium chloride (Ψ = 300MPa), Magnesium chloride (Ψ = 149MPa), Magnesium nitrate (Ψ = 86 MPa), Sodium chloride (Ψ = 39 MPa), Potassium chloride (Ψ = 23 MPa), Potassium nitrate (Ψ = 10 MPa), Potassium sulfate (Ψ = 4MPa) and distilled water to obtain total suction of approximately 0 MPa (Relative Humidity = 100%). Tests are performed at a temperature of 24 ± 1 °C. The total suction value imposed by each saline solution was measured before the test, using a dew-point chilled mirror psychrometer (the WP4C, e.g.: Cardoso et al., 2007; Leong et al., 2003).

The specimen deformations are measured in the directions perpendicular ($\varepsilon^{\perp}$) and parallel ($\varepsilon^{//}$) to the bedding. All the tested specimens are equipped with two bi-axial temperature-compensated strain gauges, two perpendicular and two parallel to the bedding, that provide strain measurement with microstrain resolution.

Cylindrical specimens were prepared (approximately diameter of 25 mm and height of 20 mm), with bedding orientation perpendicular to the axis of the cylinder. Two specimens were placed inside the desiccator (Figure 2): the first was equipped with strain gauges and used for deformation measurements; the second was used to monitor the weight evolution during each step of total suction, in order to assess the water content evolution and stabilization. A special coating was applied on the strain gauges in order to avoid possible electrical signal anomalies (e.g.: interruption of signal acquisition or drop of the recorded value), induced by the condensation of water drops when the specimen is subjected to high relative humidity.

The first value of total suction was chosen close to initial condition of the specimens after preparation (assessed with the WP4C). The specimens were subjected to a first wetting phase, in steps, from the initial state to RH = 100%. Secondly, a drying path, up to ψ = 300 MPa was performed. Lastly, the specimens were wetted again until RH = 100% was reached. At each suction step, the achievement of the equilibrium was assessed by checking the stabilization of the strains and the mass of the specimens, requiring approximately 1 week. After the equalization, the specimens were moved, in few seconds, in another desiccator prepared with the saline solution corresponding to the next suction step to impose.

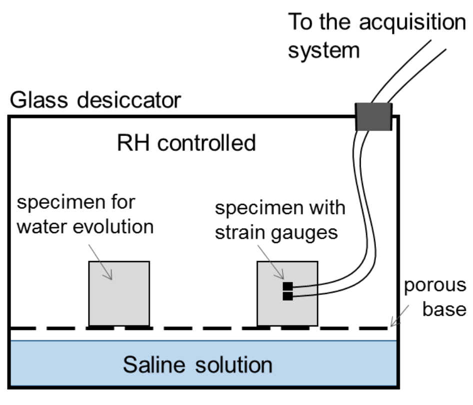

Figure 2 Simplified scheme of the adopted testing set-up: sealed glass desiccator with saline solution and tested samples.

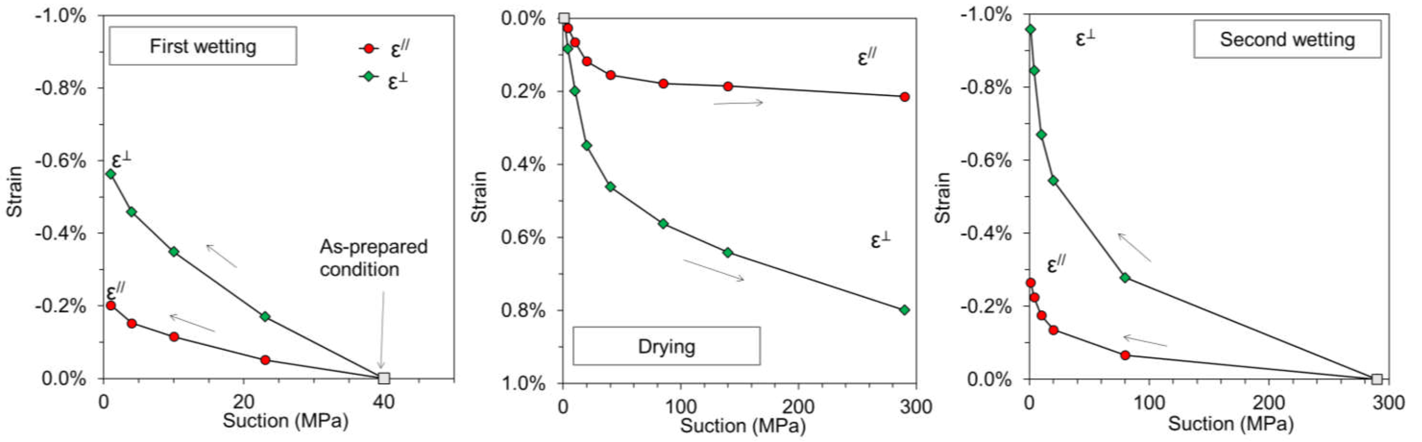

Figure 3 Strains in the direction parallel $\boldsymbol{\varepsilon}^{//}$ and perpendicular $\boldsymbol{\varepsilon}^{\perp}$ to the bedding planes, over the suction change, depicted for first wetting, drying and second wetting phase.

3 RESULTS AND DISCUSSION

The results are shown in Figure 3 in terms of developed strain in the direction perpendicular ($\varepsilon^{\perp}$) and parallel ($\varepsilon^{//}$) to the bedding, for each of the three hydraulic loading phases: the first wetting, from the initial condition (as-prepared specimen) to RH=100%; the drying, from the end of the previous path to the maximum suction applied (≈300 MPa); the second wetting, from the driest condition back to RH=100%.

As expected, the shale exhibits shrinkage upon drying and swelling upon wetting in both the directions. The strains in the two investigated directions are significantly different, both along drying and wetting paths, with the strains in the direction perpendicular to the bedding considerably higher than the orthogonal direction.

Moreover, for both directions, the strain evolution versus suction is strongly non-linear: at low suction values, the deformation rate is higher compared to the high suction range.

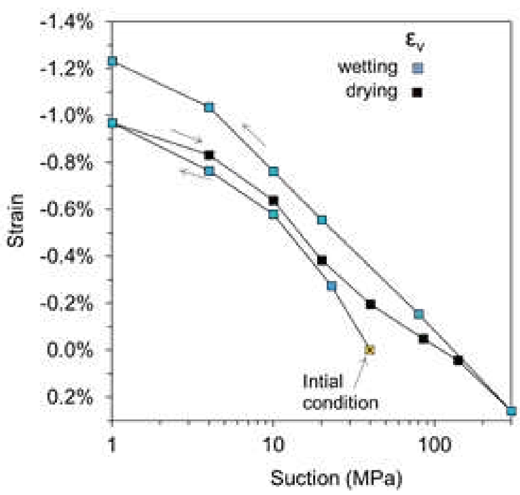

Figure 4 Volumetric strain evolution along the wetting-drying cycle.

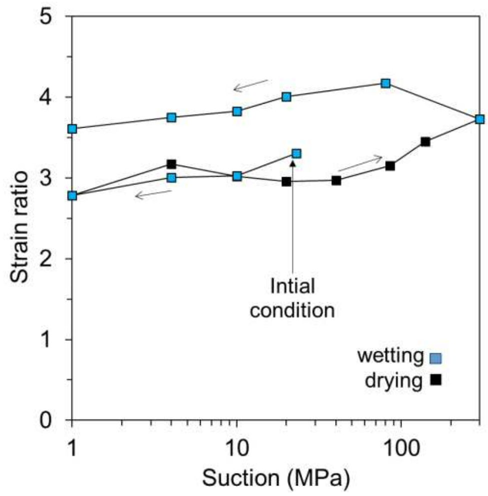

Figure 5 Ratio of the stress in the direction parallel to the direction perpendicular (stress ratio) versus the suction applied.

During drying, towards the maximum applied suction, the strain rate reduces significantly, tending to be almost zero for the direction parallel to the bedding.

Along the hydric cycle (Figure 4), the strains were found to be not completely reversible: the drying path follows the first wetting path for low suctions; then, approaching the initial suction value, the strains deviate from the initial trend, and the strain rate with the suction change is reduced. A small accumulation of swelling strains occurs, as typical for clayey materials undergoing suction cycling in highly overconsolidated conditions (e.g., Ferrari et al., 2010). Upon a complete cycle of drying and wetting, the strains perpendicular and parallel to the bedding increased by 28% and 25%, respectively. Considering the heterogeneity of the formation at the microscopic scale (almost 40% of non-clayey components), a non-uniform shrinkage-upon-drying inside the specimens can be envisaged, inducing the formation of microcracks (Wan et al., 2013; Wang et al., 2014; Yang et al., 2012).

The ratio of the strains in the direction parallel to perpendicular to the bedding ($\varepsilon^{//}/\varepsilon^{\perp}$) is reported, in Figure 5, versus the total suction applied. Along the wetting-drying-wetting path, the ratio varies between 2.8 and 4.2. It is slightly smaller (≈3) for low suction level, compared to high suction ones. Along the drying path, the ratio tends to increase; the second wetting phase presents a strain ratio that is always higher compared to the previous wetting-drying phase. The higher anisotropic ratio is compatible with the creation of microcracks preferentially oriented along the bedding direction.

4 CONCLUSIONS

The work presents experimental results on the swelling/shrinkage behavior of shallow Opalinus Clay shale upon suction cycle, obtained using an advanced technique, including total suction imposition through vapor equilibrium with saturated saline solutions, and deformation measurements by the use of strain gauges. The results highlighted a non-linear volumetric response of the shale upon suction variation, characterized by swelling upon wetting and shrinkage upon drying. The behavior was anisotropic, with the strains in the direction perpendicular to the bedding planes being 3-4 times the strains in the orthogonal direction.

The strains induced during the wetting were not completely recovered during the drying phase. During a complete drying-wetting cycle, starting from the RH=100%, the swelling strain increases of 25% and 28% in the directions parallel and perpendicular to the bedding planes, respectively. Considering the highly compacted structure and the heterogeneity in the mineralogical composition, the accumulation of swelling is attributed to the damage of the specimen and the opening of microcracks inside the material, due to a non-uniform shrinkage during the drying phase. The ratio of strains developed in the directions parallel and perpendicular to the bedding tends to increase during the drying as irreversible strain are cumulated, although it is smaller for low suction values during re-wetting.

5 ACKNOWLEDGEMENT

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6 REFERENCES

Airò Farulla, C., Ferrari, A., and Romero, E., 2010. Volume change behaviour of a compacted scaly clay during cyclic suction changes. *Canadian Geotechnical Journal*, 47, 688–703. doi:10.1139/T09-138

Alonso, E.E., Romero, E., Hoffmann, C., and García-Escudero, E., 2005. Expansive bentonite–sand mixtures in cyclic controlled-suction drying and wetting. *Engineering Geology, Issues in Nuclear Waste Isolation Research* 81, 213–226. doi:10.1016/j.enggeo.2005.06.009

Bossart, P., and Thury, M., 2008. *Mont Terri rock Laboratory*. Project, Programme 1996 to 2007 and results.

Cardoso, R., Romero, E., Lima, A., and Ferrari, A., 2007. A Comparative Study of Soil Suction Measurement Using Two Different High-Range Psychrometers, in: Schanz, T. (Ed.), *Experimental Unsaturated Soil Mechanics, Springer Proceedings in Physics*. Springer Berlin Heidelberg, pp. 79–93. doi:10.1007/3-540-69873-6_8

Ferrari, A., Airò Farulla, C., and Romero, E., 2010. On the volumetric response of a compacted clay subjected to wetting and drying cycles. *In Unsaturated Soils 4th Asia-Pacific Conference on Unsaturated Soils*, 23-25 November, Newcastle, Australia, pp. 89-94.

Ferrari, A., Favero, V., Marschall, P., and Laloui, L., 2014. Experimental analysis of the water retention behaviour of shales. *International Journal of Rock Mechanics and Mining Sciences*, 72, 61–70.

Fredlund, D.G., and Rahardjo, H., 1993. Frontmatter, *in: Soil Mechanics for Unsaturated Soils*. John Wiley & Sons, Inc., pp. i–xxiv.

Leong, E.-C., Tripathy, S., and Rahardjo, H., 2003. Total suction measurement of unsaturated soils with a device using the chilled-mirror dew-point technique. *Géotechnique,* 53, 173–182.

Minardi, A., Crisci, E., Ferrari, A., and Laloui, L., 2016. Anisotropic volumetric behaviour of Opalinus clay shale upon suction variation. *Géotechnique Letters*, 6, 1–5. doi:10.1680/jgele.16.00023

Sharma, R.S., and Wheeler, S.J., 2000. Behaviour of an unsaturated highly expansive clay during cycles of wetting and drying. *Unsaturated Soils Asia Proc. Asian Conf. Unsaturated Soils UNSAT-ASIA*, *2000*, Singapore, 18-19 May 2000, 721–726.

Wan, M., Delage, P., Tang, A.M., and Talandier, J., 2013. Water retention properties of the Callovo-Oxfordian claystone. *International Journal of Rock Mechanics and Mining Sciences* 64, 96–104.

Wang, L. L., Bornert, M., Héripré, E., Yang, D. S., and Chanchole, S., 2014. Irreversible deformation and damage in argillaceous rocks induced by wetting/drying. *Journal of Applied Geophysics*, 107, 108–118.

Yang, D.S., Bornert, M., Chanchole, S., Gharbi, H., Valli, P., Gatmiri, B., 2012. Dependence of elastic properties of argillaceous rocks on moisture content investigated with optical full-field strain measurement techniques. *International Journal of Rock Mechanics and Mining Sciences*, 53, 45–55.