Thermal issues in shales and clayrocks

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Introduction

Temperature effects in shales and clayrocks became an important issue with respect to energy management in link with radioactive waste geological disposal at great depth. The knowledge recently gained in investigating the thermo-hydro-mechanical (THM) behaviour of shales and clayrocks obviously presents a wider interest for fundamentals issues concerning clay and shale behaviour with respect to energy production, in link with gas and oil shale, as well as geoenergy storage and recovery.

Whereas advanced in-situ experiments and significant understanding of THM issues have been carried out in underground research laboratories devoted to radioactive waste disposal (e.g. Gens et al. 2007), few available laboratory data about the THM behaviour of shales and clayrocks are available in the literature. Testing shales and clayrocks requires the adaptation of soil mechanics concepts, concerning in particular the saturation procedure of initially desaturated specimens, and satisfactory drainage conditions. Inspection of literature data shows that these concepts have rarely been adopted. After presenting some specificities of the water sensitivity of claystones, some new THM devices relevant for testing shales and clayrocks are presented and some experimental data commented.

Issues concerning thermal volume changes and the thermal pressurisation of shales are discussed, with special interest devoted to plastic thermal contraction. The thermal reactivation of failure planes, of significant interest when dealing with the response of the excavation damaged zone (EDZ) around galleries and disposal cells, is also commented.

Water sensitivity

A possible illustration of the water sensitivity of shales and clayrocks can be drawn from the water retention properties of the COx claystone presented in Figure 1 and obtained using both controlled and measured suctions (see Wan et al. 2013).

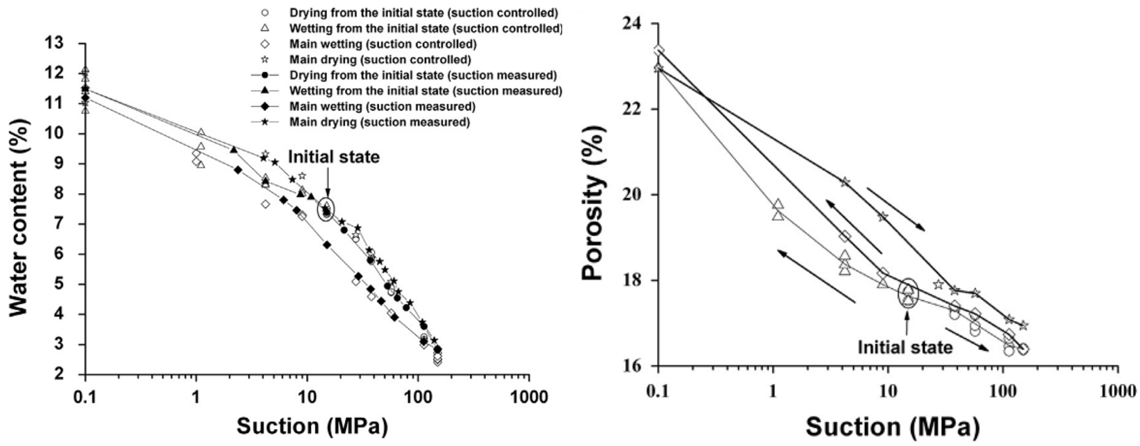


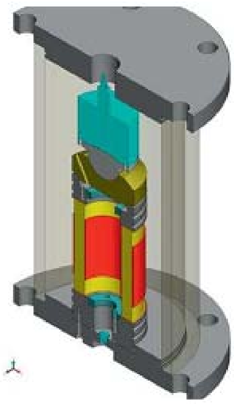
Figure 1. Water retention properties of the Cox claystone (Wan et al. 2013): changes in water content (a) and porosity (b) with respect to suction.

Starting from the initial state (degree of saturation S_r = 76%, suction s = 18 MPa, WP4 measurement), one observes a significant swelling upon wetting due to the creation and hydration of saturated cracks that appear after specimen saturation at 9 MPa suction, evidencing in claystones significant coupling between swelling and damage (see also Mohajerani et al. 2011). The curve of Figure 1b also exhibits some shrinkage upon drying.

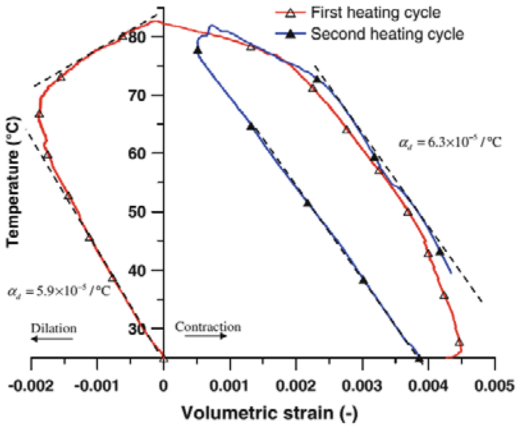
Drained and undrained thermal response of shales and clayrocks

b)

Figure **2**a (Monfared et al. 2011) presents a hollow cylinder triaxial apparatus with 60 and 100 mm internal and external diameters, respectively, with drainage ensured along the inner and outer walls of the cylinder and 70 mm height. This device allows, thanks to a drainage length reduced to 10 mm (half the thickness of the hollow cylinder) to ensure good saturation conditions within a reasonable period of time, as well as fully drained conditions if sheared at low enough stress or strain rate (0.5 kPa/mn). The specimen can also be heated and calculations indicated that a heating rate of 1°C/h ensured drained conditions.



a)

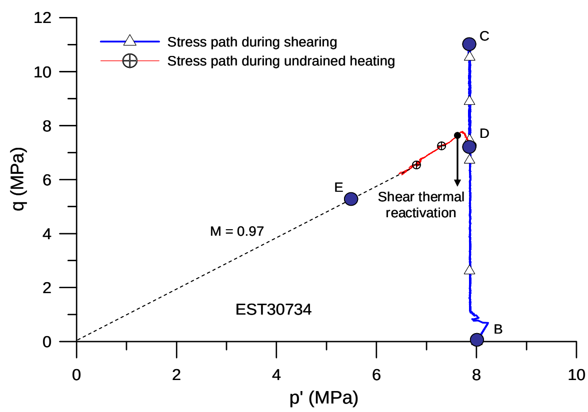


b)

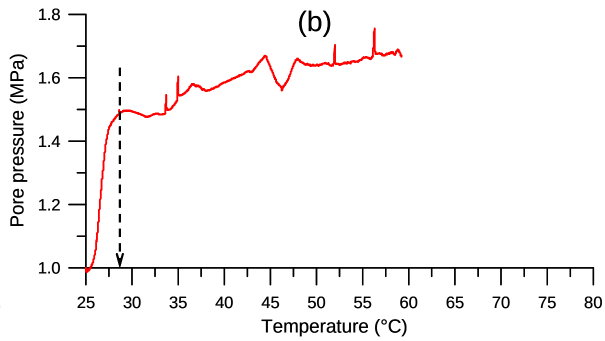
Figure 2. a) Hollow cylinder triaxial cell (Monfared et al. 2011); b) Drained thermal volume changes of Opalinus clay under in-situ stress conditions.

b)

Figure **2**b indicates that a specimen of Opalinus clay heated under drained conditions close to in-situ stress first presents a thermoelastic expansion phase (with a volumetric thermal expansion coefficient α_d = 5.9 10^{-5} /°C) followed by plastic thermal contraction at 68°C, a temperature close to the maximum temperature supported during its geological history. The subsequent drained heating test no longer shows any contraction since the highest supported temperature changed to 80°C, evidencing an interesting thermal hardening phenomenon. Note that thermal plastic contraction was also observed in the COx claystone (Mohajerani et al. 2014).



a)



b)

Figure 3. Thermally induced reactivation of a failure plane (Menaceur 2014): a) Stress path; b) Thermal pressurisation

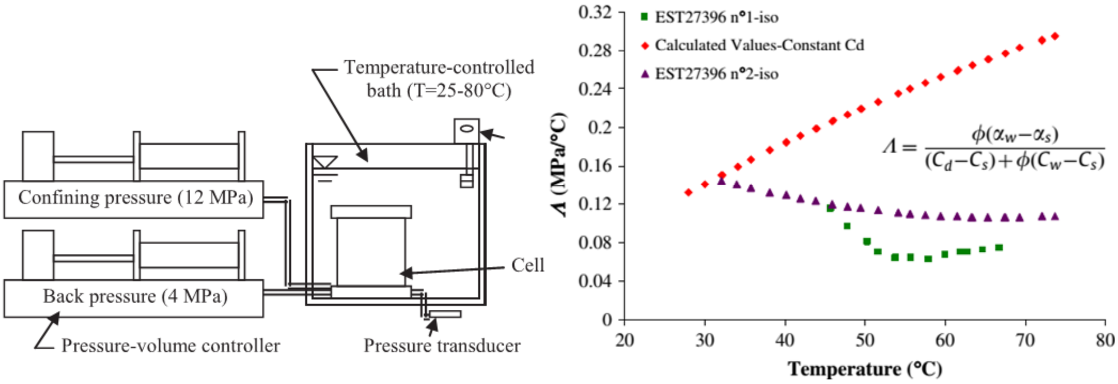
b)

Figure **3** (Menaceur 2014) shows the results of a failure obtained on a COx specimen by thermally reactivating an already existing shear plane by undrained heating. This situation concerns the response of the EDZ when submitted to temperature elevation once the waste placed in the disposal cells and this problem was one of the main concerns of the TIMODAZ European project devoted to the impact of temperature on the EDZ (Li et al. 2014). After shearing the specimen in drained conditions under constant mean effective Terzaghi stress *p'* (b)

Figure 3a), the shear stress (q) was released well below the failure criterion. Due to thermal pressurisation during undrained heating between 25 and 28°C (b)

Figure 3b), reactivation was observed with significant thermal pressurisation of pore water from 1 to 1.5 MPa. Note that a similar phenomenon was observed on the Boom clay by Monfared et al. (2012).

Thermal pressurisation is well documented by carrying out the back analysis of in-situ measurements of temperature and pore pressure (e.g. Gens et al. 2007) in underground research laboratories, but few (surface) laboratory data are available. The changes of the thermal pressurisation coefficient Λ with temperature presented in Figure 4b obtained with the device of Figure 4a are in a range compatible with other data (around 0.010 MPa/°C). The poroelastic formulation of Λ indicates that it does not only depends on the significant difference between the thermal expansion coefficient (α_i) of both water and the solid phases (with $\alpha_w >> \alpha_s$), but also of the changes in drained compressibility (C_d) with temperature. This issue of thermal pressurisation is of some importance when evaluating the undrained thermal response of the host rock in the close field but also further from the disposal cells.



a) b)

Figure 4. a) Device to investigate thermal pressurization; b) Change in thermal pressurisation coefficient with temperature (Mohajerani et al. 2012).

Concluding remarks

Experimental THM testing of shales and clayrocks is a difficult task requiring advanced and demanding techniques in which concepts from both rock and soil mechanics have to be used. Relevant data can then be obtained to better understand various aspects of waste storage or other geoenergy issues including oil and gas shale and geostorage.

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