Water Saturation Induced Strength Degradation of Callovo-Oxfordian Claystone

Zaobao Liu, Jianfu Shao and Ying Xu

Abstract It is necessary to investigate the effect of initial water content on the strength behaviors of the Callovo-Oxfordian (COx) argillite since the construction activities of underground radioactive waste repositories can induce a desaturation and a resaturation process of the hosted rock. The present work is devoted to an experimental characterization of the water induced strength degradation the COx argillite under constant strain rate loadings. Argillite samples of initial relative humidity (RH) of 98% are firstly tested at confining pressure of 4 MPa, 8 MPa and 12.4 MPa to derive a strength criterion. Then another group of tests on argillite samples with different saturation realized by relative humidity (dry, 76 and 85%) are carried out to quantify the water content induced strength degradation in claystone. It is found that both the peak and residual stress and the failure strain are correlated with the humidity level of the claystone. The results give the implications that the desaturation and re-saturation of argillite will exert influences on its surroundings in the underground repositories. Special attention should be paid to minimize the swelling effect of clay minerals and oxidation of pyrite inclusions in the argillite with water presence.

Keywords Argillite · Damage · Failure · Water degradation · Radioactive waste disposal

1 Introduction

Geological disposal is considered feasible worldwide for disposal of high-level radioactive waste. Claystone, due to their low permeability, self-sealing ability and the absence of major natural fractures, have been selected as the hosted rock for

Z. Liu (✉) · J. Shao · Y. Xu
Laboratory of Mechanics of Lille, University of Lille, 59655 Villeneuve D'Ascq, France
e-mail: zaobao.liu@polytech-lille.fr

Y. Xu
School of Mines, China University of Mining and Technology, Xuzhou 221116, China

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underground radioactive waste repositories in France. In this context, the Callovo-Oxfordian (COx) argillite, has been extensively studied during the last decades in France in the framework of the underground research laboratory CIGEO [1] to characterize its thermo-hydro-mechanical behaviors.

In the construction of underground nuclear wastes repositories, the initially saturated claystone will be subjected to various couplings such as excavation induced loadings, water and gas flow, desaturation and resaturation processes after sealing. Due to the presence of clay minerals especially the smectite, the mechanical behavior of the claystone is very sensitive to its water content [2, 3]. Thus, it is necessary to investigate the effect of RH level on the mechanical behaviors of the COx clayey rock. Experimental investigations have been reported on the mechanical and hydro mechanical behaviors of the claystone in partially saturated conditions [2–6]. It is found that the strength decreases and the clayey rock becomes more ductile when RH level increases. The initial elastic modulus also decreases with water content while Poisson's ratio is slightly affected by water content. These effects are thought inherently related to the change of microstructure in the clayey rock [7]. It is thought the desaturation and resaturation process of the clayey rock may modify the distance between the clay platelets, leading to modification of the mechanical properties of clay aggregates and thus the clayey rock [8]. Moreover, damage is found more important in claystone with lower moisture values than higher ones. The shear bands and shearing factures created during triaxial compression are related to moisture levels of the claystone [9].

This study quantifies strength degradation of the COx claystone induced by increasing saturation degree. Triaxial compression tests of three confining pressures are firstly carried out to obtain a strength criterion. The pre-peak and post-peak strength of the COx claystone of different saturation is investigated.

2 Materials, Experimental Device and Method

The tested material is cored from the underground research laboratory in Meuse/Haute-Marne of France in the Callovo-Oxfordian argillite formation. The clayey rock in microscale is constituted of three major minerals, i.e. quartz, calcite and clay minerals [10, 11]. The pores of the argillite are mainly in nanoscale [1, 12].

The rock cores of argillite, although well packaged are sometimes fractured in process of transportation and conservation due to unexpected damage as well as the oxidation induced cracking of highly active inclusions. We have encountered many fractures in the original argillite rock cores although they are protected firstly by a plastic jacket, then by a concrete confinement, and eventually by a rigid plastic package with constrains at both ends.

Preparation of argillite samples with relative large diameter is difficult since the argillite is easily damaged and fractured in process of cutting and drilling in laboratory. Argillite samples with large diameters are more likely to be influenced by the inclusions. We have to use air as coolant since the argillite is prone to splinter when contacted with water without confining pressure. Thus, the drilling of samples will produce around the drilling rig a lot of dusty particles which are very fine and harmful to the health of people. And the drilling will sometimes induce specimen cracking if there are certain pre-existing cracks or weak zone in the rock cores. Sometimes the cracks can go through the specimens, which make the samples useless. Moreover, once some expected samples are drilled from a sound rock core without fractures, they are then subjected to the tests of realizing varying water contents by placement and conservation in a small container where the RH is maintained by different brines. Due to the low permeability of argillite, the desaturation and resaturation processes in the container will take a very long time depending on the sample size. At the sample time, the desaturation or resaturation generates a gradient of water content inside the sample. Due to this gradient, there is kinematic incompatibility of swelling or shrinkage strain leading to creation of local tensile stresses. Such tensile stresses may become significant in large samples and then responsible for micro cracks. Thus, many samples are cracked due to swelling of the clay minerals as well as oxidation of organic inclusions in the container with high RH levels. Therefore, special attention should be paid to the swelling of clay minerals and oxidation of active inclusions in the claystone. In the present study, the samples are protected by a scotch tape at both ends and finally they are in a good manner for usage in tests.

The samples used in this study are drilled from the same rock core with a diameter about 37 mm and a length about 74 mm. Both sample ends are polished to be perpendicular to the sample axis once they are drilled and cut to agree with the expected size. Then, all samples are conserved in a closed container in which the RH is maintained at a given level, say 76, 85 and 98%. The temperature around the container is kept 23 °C by a central air conditioner. The samples are kept in humidity controlled containers and will not be used for mechanical tests until their mass values stabilize. The dry sample is heated before test progressively in an oven at 50 °C (2 days), 80 °C (2 days) and 105 °C (3 days) to minimize the preheating-induced cracks. The RH is taken as 0% for the dry sample, which assumes that no water is retained after successive heating.

The experimental program is devoted to characterize the damage and failure behaviors of the argillite under constant strain rate loading conditions. All the tests are realized in an autonomous and auto-compensated hydro-mechanical testing system patented to the University of Sciences and Technologies. The testing system consists of three independent loading components, respectively for deviator stress loading, confining pressure application, and interstitial pressure generation, which are assembled independently in the triaxial cell. The monitoring and acquisition of pressure/stresses, fluid pressure and/or flow rate, displacements or strain is realized by some specific transducers and recorded by a data acquisition center.

The confining pressure is applied and maintained by an ISCO D260 series pump which has a precision of 0.1 MPa, and the interstitial pressure is maintained by a gas supplier controlled by a manometer which has a precision of 0.1 MPa. When applying confining pressure in the apparatus, the samples are subjected to a hydrostatic stress state. The deviator is loaded by a rigid INSTRON mechanical loading machine. The loading and unloading of the deviatoric stress are controlled by a constant axial strain rate of $\dot{\varepsilon}_1 = 0.5 \times 10^{-5}$/s. A pair of LVDT and a radius ring measure the deformation. The axial strain ε_1 is thus obtained by the ratio between the LVDT displacement and the sample length, and the radius strain ε_3 is obtained by the ratio between the ring deformation and the sample diameter. Volumetric strain ε_v of the samples in the mechanical tests are calculated by

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_3 \tag{1}$$

The deviatoric stress q in the sample is calculated by

$$q = \sigma_1 - \sigma_3 = (F - F_f)/A \tag{2}$$

where, F is the applied force; F_f is the piston friction about 0.6 KN in the tests.

3 Mechanical Curves

The strain and deviatoric stress throughout the constant strain rate loading are shown in Fig. 1a–c for the COx clayey rock samples of the RH = 98% under three confining pressures and shown in Fig. 1d–f for the samples of three different RH values under Pc = 12 MPa.

The peak strength values of the samples are related to the RH values of the samples and will be discussed later. The axial strain at macro failure of the sample of dried, with RH = 76%, 85% and 98% are respectively 1.19%, 2.22%, 2.23% and

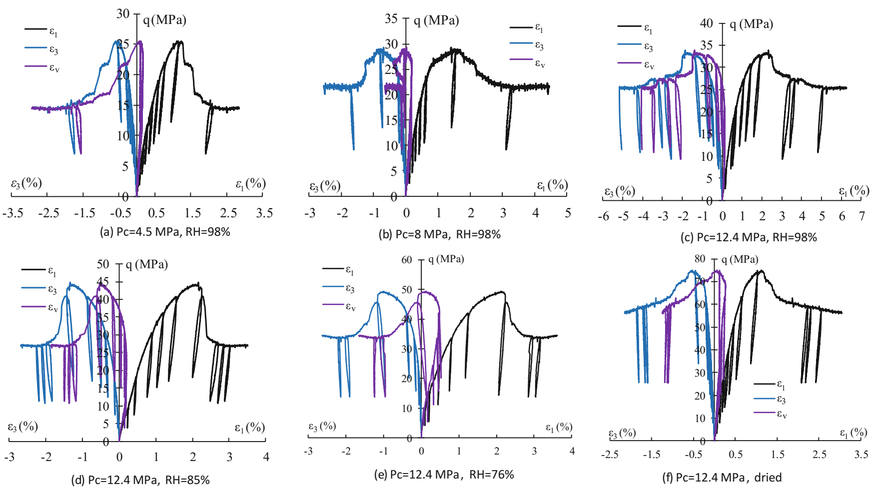


Fig. 1 Strain versus stress of claystone with different RH values

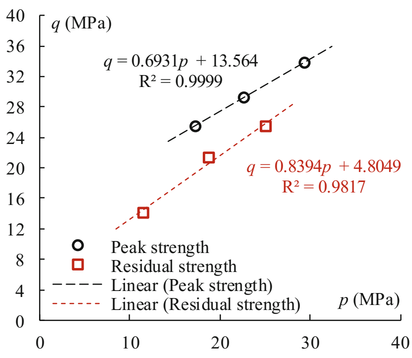
2.51%. It suggests that the strains at failures of the samples are also influenced by the RH. Samples with bigger values of RH seem to be able to bear larger deformation than the ones with lower relative humidity. Thus, high RH level can enhance the strains of the argillite samples.

Moreover, evolution of volumetric strain of the samples is influenced by its initial RH as indicated in Fig. 1, especially the onset of dilation, i.e. the turning point at which the volume strain turns from compaction to dilation in the strain-stress curves. The volumetric strain stops compacting (onset of dilation) at the deviator of q = 68.4 MPa for the dry sample (RH = 0), and respectively about q = 42.8 MPa, 26.1 MPa and 13.5 MPa for samples with RH = 76, 85 and 98% as shown in Fig. 1. Hence, the stress onset of dilation of the argillite is closely related to its RH values. The COx claystone with higher RH values arrives at its dilation onset at a much smaller stress than those with lower ones.

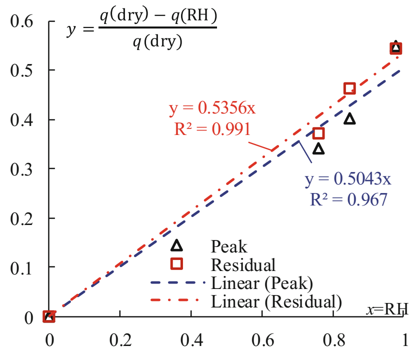
4 Strength Degradation

The detail strength properties of the claystone are shown in Fig. 2. As shown in Fig. 2a, the relation between the strength and mean stress can be well quantified by a linear function, which indicates a linear strength criterion is suitable to describe the strength behavior of the claystone of RH = 98%.

According to the evaluation results in Fig. 2a, one can calculate the cohesion c = 7.24 MPa and the friction angle $\varphi = 20.3°$, for the COx claystone at initial saturation degree of RH = 98%.



(a) q-p relation



(b) q-RH relation

Fig. 2 Strength of claystone under different Pc and saturation degree

For the degradation in mechanical strength induced by the RH, we define

$$y = \frac{q(\mathrm{dry}) - q(\mathrm{RH})}{q(\mathrm{dry})},\ x = RH - 0\%(dry) = RH \quad (3)$$

One can have a linear relationship that can describe the strength degradation properties of the claystone induced by increasing initial saturation degree at Pc = 12 MPa

$$y = mx \quad (4)$$

The degradation coefficient m is respectively 0.5043 and 0.5356 for the peak and residual strength as indicated in Fig. 2b. The linear degradation is probably induced by the weakening mechanism that the layers of the illite and smectite are easier to collapse and fall down with more water content.

5 Conclusion

Initial saturation degree has important effects on strength and deformation of the COx claystone. High initial saturation weakens argillite mechanical strength but enhances its deformation. The onset of volume dilation advances in the COx claystone with higher saturation during triaxial loading. Linear functions can quantify the claystone saturation induced strength degradation. The degradation may be induced by water weakening of interlayered structures of illite and smectite.

References

1. Andra (2012) Recherche et développement à l’Andra pour les projets de stockage. Andra, Paris
2. Yang, D., Chanchole, S., Valli, P., Chen, L.: Study of the anisotropic properties of argillite under moisture and mechanical loads. Rock Mech. Rock Eng. **46**(2), 247–257 (2013)
3. Zhang, F., Xie, S.Y., Hu, D.W., Shao, J.F., Gatmiri, B.: Effect of water content and structural anisotropy on mechanical property of claystone. Appl. Clay Sci. **69**, 79–86 (2012)
4. Bemer, E., Longuemare, P., Vincké, O.: Poroelastic parameters of Meuse/Haute Marne argillites: effect of loading and saturation states. Appl. Clay Sci. **26**(1–4), 359–366 (2004)
5. Hu, D.W., Zhang, F., Shao, J.F., Gatmiri, B.: Influences of mineralogy and water content on the mechanical properties of argillite. Rock Mech. Rock Eng. **47**(1), 157–166 (2013)
6. Zhang, F., Hu, D.W., Xie, S.Y., Shao, J.F.: Influences of temperature and water content on mechanical property of argillite. Eur J Environ Civ En **18**(2), 173–189 (2013)
7. Bornert, M., Valès, F., Gharbi, H., Nguyen Minh, D.: Multiscale full-field strain measurements for micromechanical investigations of the hydromechanical behaviour of clayey rocks. Strain **46**(1), 33–46 (2010)

8. Robinet, J.-C.: Minéralogie, porosité et diffusion des solutés dans l'argilite du Callovo-Oxfordien de Bure (Meuse, Haute-Marne, France) de l'échelle centimétrique à micrométrique. Université de Poitiers, Poitiers (2008)
9. Liu, Z.B., Shao, J.F.: Moisture effects on damage and failure of Bure claystone under compression. Geotechnique Letters **6**(3), 182–186 (2016)
10. Andra (2005) Dossier 2005: CDROM Argile—plaquettes, synthèse, tomes, référentiels et glossaire
11. Liu, Z., Xie, S., Shao, J., Conil, N.: Effects of deviatoric stress and structural anisotropy on compressive creep behavior of a clayey rock. Appl. Clay Sci. **114**, 491–496 (2015)
12. Liu, Z., Shao, J., Xie, S., Secq, J.: Gas permeability evolution of clayey rocks in process of compressive creep test. Mater. Lett. **139**, 422–425 (2015)

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