Applied Clay Science 114 (2015) 491–496

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Effects of deviatoric stress and structural anisotropy on compressive creep behavior of a clayey rock

Z.B. Liu [a], S.Y. Xie [a], J.F. Shao [a,*], N. Conil [b]

[a] Laboratory of Mechanics of Lille, UMR CNRS 8107, University of Lille, 59650, Villeneuve d'Ascq, France
[b] Andra, Chatenay Malabry, France

ARTICLE INFO

Article history:
Received 18 April 2015
Received in revised form 17 June 2015
Accepted 28 June 2015
Available online 8 July 2015

Keywords:
Creep test
Time-dependent behavior
Anisotropic creep
Argillite
Claystone
Clayey rocks

ABSTRACT

Clayey rocks are extensively investigated in France and other countries as a potential geological barrier for underground disposal of radioactive waste. In this context, it is necessary to study time-dependent deformation of clayey rocks. In this paper, we propose to perform a series of triaxial compressive creep tests on the Callovo-Oxfordian (Cox) argillite from the underground research laboratory of Andra at Bure in France. The main purpose is to investigate effects of deviatoric stress level and structural anisotropy on the creep deformation. To this end, creep tests are performed under different values of deviatoric stress for a same value of confining pressure. On the other hand, tested specimens are drilled respectively in the perpendicular and parallel directions to the bedding planes of the Cox argillite. The experimental results show that the increase of deviatoric stress enhances the creep strain which clearly exhibits an anisotropic behavior. Moreover, it is found that the inelastic creep deformation induces an increase of the long-term compressive strength of the argillite.

1. Introduction

Argillaceous rocks are the most abundant sedimentary rock type containing silt- or clay-sized particles that are less than 0.0625 mm and/or clay minerals. The argillite, more indurated than claystone or shale but not metamorphosed to slate, is a privileged candidate material in the context of radioactive waste disposal for its nature of low permeability, relatively high mechanical strength and absence of major fractures. An extensive research program has been launched by the French Agence National de Gestion des Dechets Radioactifs (Andra) that involves both experimental investigations and constitutive modeling of the Callovo-Oxfordian argillite. The present study contributes to the series of experimental investigation of the time-dependent behaviors of the argillite of the Callovo-Oxfordian stratum of MHM (Meuse/Haute-Marne) site in Eastern France.

Some previous experimental studies revealed that delayed deformations of this type of rocks were small compared to those of soft rocks, such as salt and Boom clay (Ghoreychi, 1999). Almost no viscoplastic strain was observed in this type of rock for a deviatoric stress smaller than 6 MPa (Bérest, 1987). Other tests on the Cox argillite have proven that this rock exhibits creep strain rates of the order of $3 \times 10^{-11}/s$ to $3 \times 10^{-10}/s$ when submitted to a relative deviatoric stress like 10 MPa (Valère et al., 2002), but they did not present a clear effect of the deviatoric stress. When the argillite samples were submitted to very small stresses (3 MPa for instance), the material creep strain was hidden by the clay swelling effect (Berest et al., 2001). Thus, creep responses under very small stresses were very delicate to investigate. According to other studies (Zhang and Rothfuchs, 2007), some clayey rocks exhibited a significant creep capacity even at low stresses of 0.7 to 1 MPa and the steady state creep rates observed varied in a range of $10^{-11}/s$ to $10^{-10}/s$. At the same time, temperature and saturation effects on clayey rocks were examined by a series of creep tests when samples were submitted to multistep deviatoric stresses of 2, 5, 10, 15 or 20 MPa (Gasc-Barbier et al., 2004). Their results showed that the argillite creep response was sensitive to the loading history, saturation degree as well as the temperature, but no clear conclusions were identified due to the variability of tested samples used in their tests. They also found that the creep strains trended to stabilize after 5–10 days of mechanical loading depending on applied deviatoric stress level. On the other hand, indenter studies on the Cox argillite showed that the creep strain of this material was likely linked to the deformation of clay minerals acting as the potential weak zones (Gratier et al., 2004). Thus, it was very important to consider the mineral composition effect of the argillite when discussing their mechanical responses.

More recently, multi-stage creep tests highlighted the existence of a stress threshold below which creep strains stabilized (Fabre and Pellet, 2006; Yang et al., 2011). But, their results are not extensive enough to draw definitive conclusions. Also, the multistep loading path was quite complex to interpret in terms of deviatoric stress level effect on the creep strain due to the successive plastic hardening mechanism during the creep tests. The water content and structural anisotropy of

* Corresponding author.
E-mail address: jian-fu.shao@polytech-lille.fr (J.F. Shao).

http://dx.doi.org/10.1016/j.clay.2015.06.039
0169-1317/

the clayey rock were also proven to have an important effect on their mechanical responses (Zhang et al., 2012) by mini compression tests and micro indentation tests. The evolution of porosity and creep response of the argillite were revealed by gas permeability tests in process of creep test (Liu et al., 2014). The results showed that the gas permeability in steady creep trends to increase though the strains trend to stabilize. The temperature and material anisotropy were identified to have important influence on the mechanical properties of the clayey rocks (Masri et al., 2014). Some other works were reported on the instantaneous mechanical properties of COx argillite by different authors (Hu et al., 2013; Huang et al., 2013; Yang et al., 2013; Zhang et al., 2013). These works have confirmed that the clayey rock mechanical properties should be influenced by the factors such as water saturation degree, mineral composition, temperature, loading history, and structural anisotropy.

In this context, the present experimental program, in complementary with the former tests, aims to investigate the impact of deviatoric stress level on the argillite creep strain by a series of one-step creep tests. To maximally avoid the influence of initial relative humidity, temperature effect, clay swelling, variation of mineral composition and loading history in the present test program, these conditions are technically kept the same for all tests to well characterize the creep response induced by the applied different deviatoric stresses under the same confining pressure. Moreover, the anisotropic creep response will also be investigated by comparing creep test results of samples perpendicular and parallel to the bedding planes of the argillite.

2. Material and experimental program

2.1. Material characterization and sample preparation

The argillite sample used in our tests is originally drilled from the Callovo-Oxfordian stratum of MHM (Meuse/Haute-Marne) site in France at the depth about 512.75 m with an identification number EST30442 provided by Andra. The mineral composition and porosity of the material are illustrated respectively by the SEM image in Fig. 1 and the pore size distribution diagram in Fig. 2 (Robinet, 2008). At the mesoscopic scale, the Cox argillite is mainly composed of clay minerals, carbonate and quartz grains. The average proportion of each constituent phase is about 40% (±15%) quartz, 34% calcite and 26% clay minerals. However, the mineralogical compositions can significantly vary with the depth. The composition of clay phase (<2 μm) approximately includes 40% illite, 30% kaolinite, 5% chlorite, and 25% swelling minerals (such as smectite and interstratified). The mineral composition of the clayey rock was obtained by using X-ray diffraction technique.

The specimens used in the experimental program is cored to be 40 mm in length and 20 mm in diameter to obtain a well-mannered mechanical behavior from the original core EST30442 of size 300 mm in length and about 78 mm in diameter. The samples are cut by a diamond saw and polished on both ends to obtain well-mannered

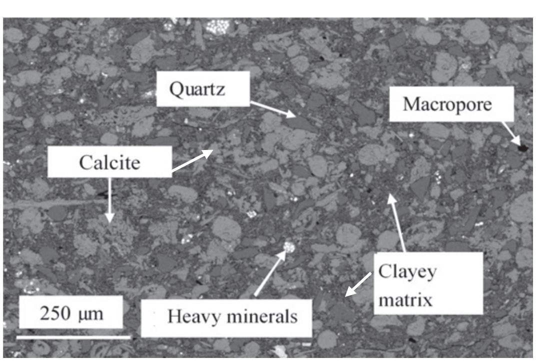

Fig. 1. Mineral composition of the Cox argillite by SEM image. Picture from Robinet (2008).

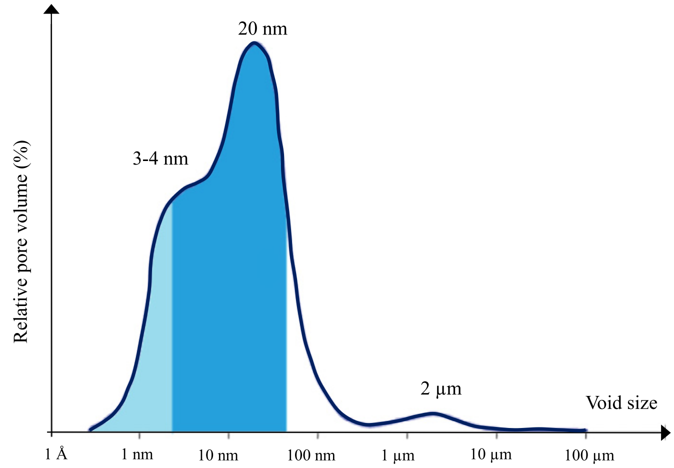

Fig. 2. Pore size distribution of the Cox argillite. Data from Robinet (2008).

specimens for mechanical tests. During all these operations, the plastic film is used to protect the specimens from drying to avoid cracks. In total, 13 specimens are finally prepared with well manner from the core EST30424 with 10 in perpendicular direction and 3 in parallel direction to the bedding planes as given in Table 1. Another specimen was made from the core EST50330 to identify the creep behavior in relative low deviatoric stress level as a supplement. Then, the specimens are kept and partially saturated in a closed container of 59% relative humidity maintained by the KI solution for more than one month until the masses of specimens become stable. In this way, all specimens can be thought with the same degree of saturation since they are drilled in similar size from the same rock core where the variation of mineral composition can be minimized.

2.2. Experimental program

The autonomous and auto-compensated hydromechanical coupling system (Fig. 3) designed at the Laboratory of Mechanics of Lille (LML) is used to realize the creep tests. All tests are conducted with the same confining pressure in a thermally insulated room at constant temperature (20 ± 0.5 °C) maintained by an air-conditioner in order to well identify the effect of deviatoric stress on creep responses. To avoid influence of loading path, all specimens, after being sealed by a plastic

Table 1
Identification of specimens and experimental program.

No.	Specimen direction	Length (mm)	Diameter (mm)	Deviatoric stress level (percent to peak stress)	
				Planned	Actual
EST30442-1	Perpendicular	40.58	19.74	70%	60%
EST30442-2		40.59	19.70	80%	77%
EST30442-3		39.36	19.70	90%	Failed
EST30442-4		39.93	19.68	50%	51%*
EST30442-5		40.9	19.70	Reference triaxial test	
EST30442-6		39.07	19.71	85%	82%
EST30442-7		39.9	19.74	90%	Failed
EST30442-8		39.96	19.70	70%	System error
EST30442-9		40.12	19.70	90%	85%
EST30442-10		40.74	19.70	90%	Failed
EST30442-11	Parallel	40.46	19.65	90%	Failed
EST30442-12		40.25	19.67	Reference triaxial test	
EST30442-13		39.63	19.70	90%	82%
EST50330-1		38.34	19.64	50%	47%

* Value calculated with the peak stress in the reference triaxial test due to unrecorded accidental failure.