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Effects of relative humidity and mineral compositions on creep deformation and failure of a claystone under compression

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ABSTRACT

During the last decades, clayey rocks have been widely investigated in many countries as a potential geological barrier for underground disposal of radioactive waste. Clayey rocks are heterogeneous materials at a micrometer scale. Mechanical behaviors of clayey rocks are generally influenced by mineralogical compositions and/or water content. A large number of studies have been so far performed on short term behaviors of clayey rocks. However, very limited data are available on time-dependent deformation and failure process. This paper is devoted to investigating the effects of relative humidity and mineralogical compositions on creep deformation of a hard claystone and the possibility of creep failure is studied. Influences of confining pressure and structural anisotropy are also investigated. For this purpose, four groups of creep tests are carried out under triaxial compression conditions on claystone samples drilled from the underground research laboratory at Bure in France. In the first group, creep tests are performed on samples with three different values of relative humidity (RH, 59%, 85% and 98%) under a confining stress of 6 MPa. In the second group, claystone samples with different mineralogical compositions drilled from different geological unities are investigated. In the third group, for a selected value of relative humidity (RH 59%), triaxial creep tests are performed under different values of confining stress (2, 6 and 12 MPa). Finally, effects of structural anisotropy of claystone at HR = 59% are investigated by considering samples respectively drilled in parallel and perpendicular directions to the bedding planes. A series of new experimental data are obtained and analyzed. It is found that at the tested level of relative humidity the confining stress seems to increase creep strain and rate of the claystone. The clay minerals especially the smectite can play an essential role in time-dependent deformation and increase creep strain of the claystone at RH = 59%. Further, creep strains are more important under higher values of relative humidity than lower ones. In very few cases, the failure due to acceleration creep was observed but for high deviatoric stress level. The experimental data obtained in this work can be used as a background for numerical modeling of time-dependent behavior of re/desaturated clayey rocks in the context of geological disposal of radioactive waste.

1. Introduction

Clayey rocks are intensively investigated in many countries such as France, Swiss, Belgium and Sweden as a potential geological barrier for underground radioactive waste disposal. An underground research laboratory (URL) at the Meuse/Haute-Marne Center (CMHM) has been constructed at Bure in France by the French National Agency for Radioactive Waste Management (Andra). The URL is situated in the Callovo-Oxfordian (COx) claystone layer.[1,2] During the last decades, an extensive research program has been launched by Andra involving both experimental investigations and modeling studies. And a new investigation phase is undertaken for a deeper characterization of short- and long- term thermo-hydro-mechanical behaviors of the COx claystone. The present study is a part of this research program.

The excavation and ventilation of underground drifts can induce an unsaturated zone in the claystone formation and a damage zone around the galleries.[3] The existence of such a damaged zone may affect both short and long term hydromechanical behaviors of claystone. It is shown that the mechanical behavior of COx claystone is sensitive to water content.[4–7] Therefore, it is necessary to investigate both short- and long-term mechanical behaviors of the host claystone under different saturation conditions to verify the good functionality of the excavation damaged zone.

Instantaneous mechanical behaviors of the COx claystone have been investigated by different laboratory tests, such as oedometric compression, mini compression, micro indentation, uniaxial and triaxial

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Table 1
Geometry of samples, testing program and conditions.

Rock core	Sample NO.	Direction	D (mm)	L (mm)	Pc (MPa)	RH	Differential creep stress q (MPa)	q_{peak} (MPa)	Actual creep level q/q_{peak}
EST44311	B01	⊥	19.8	40.12	6	59%	$q=40.1$	44.2 (Reference)	One-step creep failure
	B03		19.78	40.02		85%	$q=30.1$	34.2 (Reference)	
	B06		19.81	40.10		98%	$q=26.1$	29.5 (Reference)	
	B09		19.79	39.96	12	59%	$q=52.3$	59.7(Reference)	
EST30442	C2	⊥	19.72	40.50	6	59%	36.2	56.9	64%
	C6		19.70	39.37			44.9	56.4	80%
	C8		19.75	40.34			Triaxial reference $q_{peak}=442$		
	P1	//	19.77	40.15			Triaxial reference $q_{peak}=405$		
	P3		19.73	39.69			36.1	45.3	80%
EST50330	L1	//	19.74	39.48	6	59%	Triaxial reference $q_{peak}=324$		
	L3		19.76	37.85			35.5	43	83%
	L4		19.70	35.08			22.3	38.3	58%
	L12		19.74	33.31			33.3	48.1	69%
	L7	⊥	19.64	38.34			20.4	44.2	46%
	L8		19.81	40.13			39.3	49.3	80%
	L9		19.75	37.62			Triaxial reference $q_{peak}=354$ MPa		
EST44300	A03	⊥	19.08	37.82	12	59%	Triaxial reference		$q_{peak}=62.6$
	A04		19.15	38.06	2				$q_{peak}=33.4$
	A22		19.13	39.30	6				$q_{peak}=46.6$
	A02		19.22	36.76	6		39.8	49.6	80%
	A07		19.16	39.14	12		45.6	57.3	80%
	A16		19.10	39.08	2		27.8	35.6	78%

(Pc: Confining pressure; D: Diameter; L: Length; RH: Relative humidity; q_{peak}: Peak strength; Interstitial pressure is 0.95 MPa)

compression, triaxial extension.[5–16] Without giving an exhaustive review of all previous studies, just mentioning a number of tests that have been devoted to investigate effects of water content, mineral composition, structural anisotropy and temperature on mechanical behaviors of the COx claystone. In particular, these studies have shown that the instantaneous mechanical properties of the COx claystone were clearly affected by water saturation degree.[6,7,17] For instance, the elastic modulus and compressive strength decreases with the increase of water content which probably due to the process of resaturation which damages the samples. The behavior of claystone becomes more brittle under lower saturation degree i.e. after desaturation of samples. Those results give a basic understanding of the instantaneous behaviors of the COx claystone in the excavation damaged zone.

A number of experimental studies have also been performed on time-dependent behaviors of the COx claystone.[18–25] Some results have suggested that the creep strain rate of the claystone could reach an order of magnitude of $10^{-11}\sim10^{-10}$/s under low differential stress. The similar magnitudes are also observed with in situ measurement after excavation of galleries.[26] The environmental factors such as water saturation degree and temperature also have an important influence on creep deformation of the claystone. The creep deformation of claystone is found also sensitive to loading history, differential stress level as well as structural anisotropy.[22,27] In some studies, the existence of a stress threshold below which creep strains stabilize has been evidenced by multi-step creep tests[23,28–30] and confirmed by one-step creep test.[27] It was found that creep strain rates of the COx claystone become lower than 10^{-10}/s and has a decreasing trend after 3–10 days of loading depending on differential stress level and water content of sample. However, it is very difficult to realize tertiary creep test on the COx claystone by one step creep test, and few results have been obtained so far very. The existence of a creep rate threshold above which the tertiary creep can occur is still an open issue. Therefore, further experimental studies are still in need for a better understanding of creep behaviors of the COx claystone in the excavation damaged zone.

The objective of the present study is to complete existing results, and in particular, to investigate effects of resaturation and desaturation by controlled relative humidity, mineralogical compositions and confining stress on time-dependent strains of the re/desaturated COx claystone. The experimental results can help to evaluate the creep deformations of the COx claystone in the excavation damaged zone at the URL at the CMHM center.

2. Material and sample preparation

The claystone samples tested in the present work are cored in the URL at Bure. At the micrometer scale, the COx claystone is mainly constituted of clay minerals, calcite, quartz and other secondary minerals. The average pore size is about some ten nanometers[31,32] and the majority of pores are inside the clay minerals. The average distribution of mineral groups in the claystones throughout the whole formation is clay fraction (phyllosilicates) ~42 ± 11% of the rock, carbonates ~30 ± 12% of minerals, ectosilicates ~25 ± 8% of minerals; and ancillary minerals constitute less than 4%.[4] Mineralogical analyses show the mineral content exhibits low variability in the bed plane but significant perpendicular to the bedding. The COx clay-rich rock porosity lies between 14% and 20% at the URL site and is close to 18% at the URL main level,[33] and natural water content ranges between 5% and 8%.[26]

The COx claystone geological layer can be vertically divided into three lithostratigraphic units,[34] i.e. the argillaceous rich unit (UA), the transition unit (UT) and the silty carbonate-rich unit (USC). There are also three subunits in the UA, i.e. UA1, UA2 and UA3, due to variation of physical and geological properties. The rock cores tested in this paper are drilled from different unities so that we can evaluate the effects of mineralogical compositions.

The tested specimens have 40 mm in length and 20 mm in diameter and are drilled from original rock cores of 300 mm in length and about 79 mm in diameter. The samples are cut by a diamond wire saw and polished at both ends to obtain perpendicularity of sample ends to axis for laboratory tests. During all these operations, plastic films are used to minimize desaturation of the specimens. The list of tested samples with their geometry is given in Table 1. Due to the difficulty to obtain a large number of good quality samples from a single rock core, in total, four cores were used in the present study.

The samples after cored for laboratory tests are inevitably desaturated although carefully protected. At the moment, we give estimation of the properties of claystone not with the fully saturated samples due to the uncertainties in property change of the water-sensitive claystone