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Investigating the swelling pressure of compacted crushed-Callovo-Oxfordian claystone

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ABSTRACT

This paper presents an experimental study on the swelling pressure of heavily compacted crushed Callovo-Oxfordian (COx) claystone at a dry unit mass ρ_d = 2.0 Mg/m^3 using four different methods: constant-volume, swell-reload, zero-swell and adjusted constant-volume method. Results show that the swelling pressure varies in the range of 1–5 MPa and depends significantly on the test method. From the constant-volume tests, it is observed that the swelling behavior during wetting is a function of the suction and depends on both the hydration paths and wetting conditions (e.g. vapor-wetting or liquid-wetting). The swelling pressure decreases significantly with saturation time. To identify the microstructure changes of specimens before and after wetting, mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) tests were performed. It is observed that, after wetting, the large inter-aggregate pores observed in the as-compacted specimen are no longer apparent; the whole pattern is characterized by a general swell of hydrated clay particles, rendering the soil more homogenous. Results from MIP indicated that wetting caused a significant reduction of the entrance diameter of the dominant inter-aggregate pores from 2.1 to 0.5 μm whereas intra-aggregate pores were not significantly influenced.

1. Introduction

Deep clay or claystone formations are considered as potential host rock for radioactive waste disposal in many countries such as Belgium, Germany, France, Japan and Switzerland. In order to ensure the overall safety of the storage system, it is of prime importance to develop a good understanding of the clay properties involved for different time scales: i.e. during construction of the repository as well as its long-term isolation performance (Landais and Aranyossy, 2007). In addition to the coupled thermo-hydro-mechanical behavior of the host rock, the engineering properties of backfilling/sealing materials are also an important issue to investigate because these materials play a critical role in reducing migration of water, gas and radionuclides to an acceptable low level.

In the past decades, bentonite has been widely studied as backfilling and sealing material because of its low permeability, adequate self-sealing potential and high water retention capacity (Marcial et al., 2002; Lloret et al., 2003; Tang and Cui, 2005; Hoffmann et al., 2007; Tang et al., 2008a, 2008b).

The use of crushed excavated COx claystone as a possible backfilling/sealing material to isolate the waste canisters from the concrete retainment and the access gallery has been considered as a possible alternative by the French Radioactive Waste Management Agency (ANDRA) in the Underground Research Laboratory (URL) excavated at a depth of 445–490 m in Callovo-Oxfordian (COx) claystone at Bure (Eastern France, Lebon and Mouroux, 1999), The main advantages of this option are: (i) recycling excavated COx claystone as sealing material reduces the negative environmental impact; (ii) replacing commercial bentonite by excavated COx claystone reduces financial costs; (iii) there is no problem of mineralogical and physico-chemical incompatibility between the host rock and the backfilling/sealing material.

It is expected that once the backfilling/sealing material is installed, pore water from the host rock will infiltrate the compacted claystone, thereby causing it to expand and develop swelling pressure under nearly constant volume conditions. This swelling pressure should be high enough to ensure sealing efficiency. Also, the swelling pressure of the hydrated compacted claystone should not exceed the in situ principal minor stress (about 7 MPa – after Wileveau et al., 2007) so as to ensure satisfactory mechanical stability. It is therefore important to study in detail the swelling properties of the compacted crushed claystone. Since the pre-compacted backfilling/sealing blocks will be subjected to hydromechanical conditions once installed, the study of the

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swelling behavior must be conducted under different boundary conditions. In this investigation, four methods, namely a constant-volume method carried out in a specifically designed new cell, a swelling–reloading method, a zero-swell and an adjusted constant-volume method were respectively employed to evaluate the swelling pressure of highly compacted crushed COx claystone in the laboratory. Different hydro mechanical boundary conditions were applied to the specimens to simulate the possible in situ confinement and wetting process. In addition, long-term tests were carried out to study time effects (Delage et al., 2006). The microstructure changes of the specimens before and after wetting were also analyzed by performing mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) tests.

2. Material

The Callovo-Oxfordian (COx) claystone from the Bure site considered here contains 40–45% clay minerals (illite–smectite interstratified minerals being the dominant clay minerals), 30% carbonates and 25–30% quartz and feldspar. The in situ water content is 2.8–8.7%, the wet unit mass is 2.32–2.61 Mg/m^3 and the specific gravity is 2.70 (Fouché et al., 2004).

COx claystone blocks obtained during excavation were air-dried and crushed to powder at an initial water content of 2.8%. The grain size distribution of the powder determined by dry sieving is presented in Fig. 1. In order to obtain a higher water content, a quantity of powder was put in a hermetic chamber where the relative humidity was maintained at 91.3% at a temperature of 20 °C (corresponding to a suction of 12.6 MPa) by allowing vapor circulation of saturated $ZnSO_4 \cdot 7H_2O$ solution (Delage et al., 1998). Once equilibrium was reached, the powder water content was found to be 6.4%.

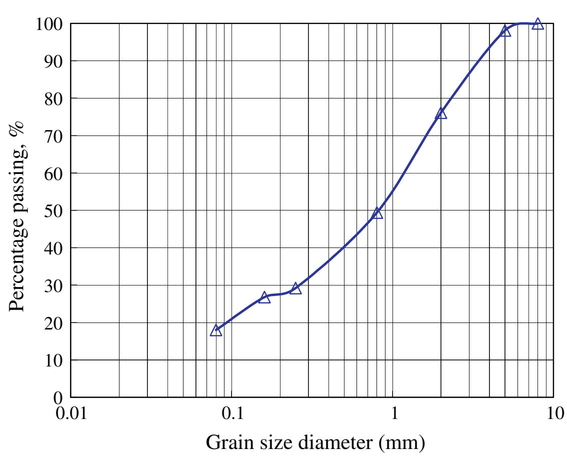

Fig. 1. Grain size distribution of the crushed COx claystone powder.

3. Experimental methods and test program

To determine the soil swelling pressure in the laboratory, the COx powder was first compacted statically to a dry unit mass of 2.0 Mg/cm^3 in an oedometer cell. The swelling pressure of the compacted COx sample was then measured using four methods: constant-volume, swell-reload, zero-swell and adjusted constant-volume method respectively. Details of each method are presented below and the test program is summarized in Table 1.

3.1. Constant-volume method

Traditionally, constant volume tests are performed based on the strain-controlled technique (Azam et al., 2000; Tripathy et al., 2004; Hoffmann et al., 2007). There are two strain-controlled techniques for constant volume conditions. The first consists in applying a small incremental load on the specimen in the oedometer cell and to prevent, when the specimen is wetted, any vertical expansion by progressively loading the sample. Once no more expansion is observed upon wetting, the final total load applied is defined as the swelling pressure of the soil (Al-Mhaidib, 1998; Al-Shamrani and Dhowian, 2003; Thompson et al., 2006; Villar and Lloret, 2008). The second method consists in preventing any vertical movement by using a rigid reaction frame and in measuring the swelling pressure with a force transducer (Lloret et al., 2003; Aiban, 2006; Hoffmann et al., 2007; Tang et al., 2011). In reality, it is difficult to maintain a strictly constant volume condition – the measured swelling pressure is influenced by many factors. In the former strain-controlled technique, each incremental load corresponds to a soil compression, giving rise to changes in soil microstructure that affect the swelling pressure. The swelling pressure determined is therefore very sensitive to the load increment and the loading rate. Moreover, in order to bring the specimen back to its initial volume, it is necessary to overcome the friction between soil specimen and oedometer ring; that results in overestimation of the swelling pressure. In the latter constant volume technique, Tang et al. (2011) found that the "constant volume" condition depends significantly on the stiffness of the load cell and of the whole device. The corresponding swelling pressure error can reach 1–2 MPa. Pejon and Zuquette (2006) pointed out that very small changes in specimen height (e.g. a strain of 0.5%) would lead to significant swelling pressure changes (e.g. 45–60%). Thus, the measurement of swelling pressure by the methods mentioned above should be regarded as indirect measurements only. Up to now, owing to difficulties related to testing devices, data on direct measurement of the swelling pressure under constant volume conditions are scarce. For this reason, a new constant volume cell has been developed that allows the swelling pressure to be measured without any strain adjustment and any effect of the stiffness of the testing device.

Table 1
Tests program.

Test method	Test No.	Initial water content (%)	Apparatus	Specimen size (mm)	Wetting condition
Constant-volume	T1	2.8	Fig. 4	$H = 10$, $D = 70$	Suction controlled: $s = 57$, 38, 9, and 0 MPa
	T2	2.8	Fig. 4	$H = 10$, $D = 70$	Suction controlled: $s = 57$ and 38 MPa
	T3	2.8	Fig. 4	$H = 10$, $D = 70$	Suction controlled: $s = 38$ and 0 MPa
	T4	2.8	Fig. 4	$H = 10$, $D = 70$	Suction controlled: $s = 9$ and 0 MPa
	T5	2.8	Fig. 4	$H = 10$, $D = 70$	Suction controlled: $s = 0$ MPa
Swell-reload	T6	2.8	Fig. 5	$H = 10$, $D = 38$	Injecting distilled water
Zero-swell	T7	2.8	Fig. 5	$H = 20$, $D = 50$	Injecting distilled water
Adjusted constant-volume	T8-1 T8-2	2.8	Fig. 6	$H = 20$, $D = 50$	Injecting distilled water
	T9	2.8	Fig. 6	$H = 20$, $D = 50$	Injecting distilled water
	T10	6.4	Fig. 6	$H = 20$, $D = 50$	Injecting distilled water