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The stress–strain–permeability behaviour of clay rock during damage and recompaction

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ABSTRACT

Characterisation and understanding of the stress–strain–permeability behaviour of a clay host rock during damage and recompaction are essential for prediction of excavation damaged zone and for assessment of its impact on the repository safety. This important issue has been experimentally studied in triaxial compression tests on the Callovo-Oxfordian clay rock in this study. The samples were sequentially loaded by (1) hydrostatic precompaction to close up sampling-induced microcracks, (2) applying deviatoric stresses to determine damage and permeability changes, and (3) recompression along different loading paths to examine reversibility of the damage. The critical stress conditions at the onset of dilatancy, permeability percolation, failure strength, and residual strength are determined. An empirical model is established for fracturing-induced permeability by considering the effects of connectivity and conductivity of microcracks. The cubic law is validated for the variation of permeability of connected fractures with closure. The experiments and results are also presented and discussed.

1. Introduction

Excavation of underground openings leads to a redistribution of the rock stress, particularly to a high concentration of deviatoric stresses in the surrounding rock where radial stresses are decreased. This results in fractures and permeability increase in the near-field if the damage and failure criteria of the rock are violated. As observed in the Underground Research Laboratories (URLs) at Mont Terri in Switzerland (Bossart et al., 2004; Blümling et al., 2007) and at Bure in France (Armand et al., 2014), the excavation damaged zone (EDZ) in the Opalinus and Callovo-Oxfordian argillaceous formations is developed near drift walls and the permeability increases over several orders of magnitude. However, reconsolidation of the EDZ can be expected due to convergent compression of the surrounding clay rock, the increasing resistance of the backfill/seal materials, and additionally the water-induced swelling of clay minerals into fracture interstices. For reliable predictions of the EDZ development and for an assessment of its impact on the long-term safety of a radioactive waste repository, it is necessary to establish a robust database and adequate constitutive models for description of the hydromechanical behaviour of the host rock.

During the last decade, the hydromechanical behaviour of the Callovo-Oxfordian and Opalinus clay rocks, which are being investigated as the potential host rocks for radioactive waste repositories (Nagra, 2002; Andra, 2005), has been extensively studied in laboratory experiments. Most of the investigations focused on the stress–strain–permeability behaviour of the clay rocks during the pre-failure phase (Renner et al., 2000; Zhang and Rothfuchs, 2004, 2008; Corkum and Martin, 2007; Naumann et al., 2007; Popp and Salzer, 2007; Jobmann et al., 2010; Amann et al., 2014). The knowledge of the pre-failure behaviour is useful for the evaluation of the intensity and extent of the EDZ as well as for an adequate design of the support measures for the openings. More important is, however, the post-failure behaviour of the damaged host rock for prediction of the reconsolidation process of the EDZ during the long-term post-closure phase of the repository. This important issue has been not yet intensively investigated and so far there are only very limited data available (Davy et al., 2007; Bock et al., 2010; Zhang, 2013, 2015). In order to characterise the complete pre- and post-failure behaviours of clay rock, a new series of laboratory experiments has been performed on the Callovo-Oxfordian claystone. The experiments and results are also presented and discussed in this paper.

2. Preparation and characterisation of samples

Core samples were extracted from the Callovo-Oxfordian argillaceous formation at the −490 m main level of the Meuse/Haute-

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Marne URL (MHM-URL) in France. The boreholes were drilled horizontally parallel to the bedding planes. In order to prevent desaturation and damage, the drilled cores were confined in special cells developed by Andra (2005) and stored in a climate-controlled room at 22 °C before testing. Cylindrical samples were carefully prepared from the cores to a size of 70 mm diameter and 140 mm length by cutting and smoothing the surfaces in a lathe. Because of the high sensitivity of the clay rock to changes of the environment, microcracks were unavoidably induced by sampling. They mostly oriented along the bedding planes.

The samples were characterised by measurement of their mineralogical composition and physical properties. On average, the claystone at the sampling locations contains 27–42% clay minerals, 28–38% carbonates, 26–36% quartz and small amounts of other minerals (Andra, 2005). The physical properties obtained from more than 30 samples are: grain density = (2.7 ± 0.01) g/cm^3, bulk density = (2.4 ± 0.02) g/cm^3, porosity = (16.8 ± 1)%, water content = (6.5 ± 0.8)%, and degree of water saturation = (90 ± 6)%. It has to be pointed out here that the disturbed samples are not quite representative for the intact natural rock that is water-saturated and highly-consolidated under the geologically confined conditions. For gathering more representative data for the intact rock, the quality of the samples has to be improved. This was done by hydrostatically compressing the samples up to the in situ rock stress and even higher stresses.

3. Testing method and procedure

Triaxial compression tests were carried out on the samples to measure various mechanical and hydraulic parameters. Fig. 1 illustrates schematically the test principle. The sample is inserted in a rubber jacket and covered between two load pistons, in which piezo-electric wave transducers are installed for ultrasonic wave measurement to detect changes in the inner structure of the sample. Axial strain ε_1 is monitored using a linear variable differential transducer (LVDT) installed outside the cell, while radial strain ε_3 is recorded using a circumferential extensometer chain mounted around the sample. Based on the measured axial and radial strains, the volumetric strain can be obtained by $\varepsilon_{\mathrm{v}} = \varepsilon_1 + 2\varepsilon_3$. The hydraulic system allows monitoring fluid flow through the sample in the axial direction. In the tests, nitrogen gas was injected at the bottom at a constant pressure of 0.2 MPa and the outflow was determined by feeding the gas at the top into a burette at atmospheric pressure. To ensure gas flow through the generated fractures in case they did not link the end faces of the sample directly, two thin filter sheets were inserted between sample and jacket in the upper and lower sections along about 1/6 of the sample length each, which was estimated assuming a fracture inclination angle of about 30° to the major principal stress σ_1. From the steady-state gas flow, the apparent gas permeability is obtained according to Darcy's law for compressive media:

$$k = 2\mu \frac{p_{\mathrm{o}} q}{p_{\mathrm{i}}^2 - p_{\mathrm{o}}^2} \frac{l}{A} \tag{1}$$

where k is the gas permeability (m^2), q is the flow rate of the gas (m^3/s), μ is the dynamic viscosity of the gas (Pa s), l is the effective length of the sample (m), A is the cross section of the sample (m^2), p_{i} is the inlet pressure (Pa), and p_{o} is the outlet pressure (Pa).

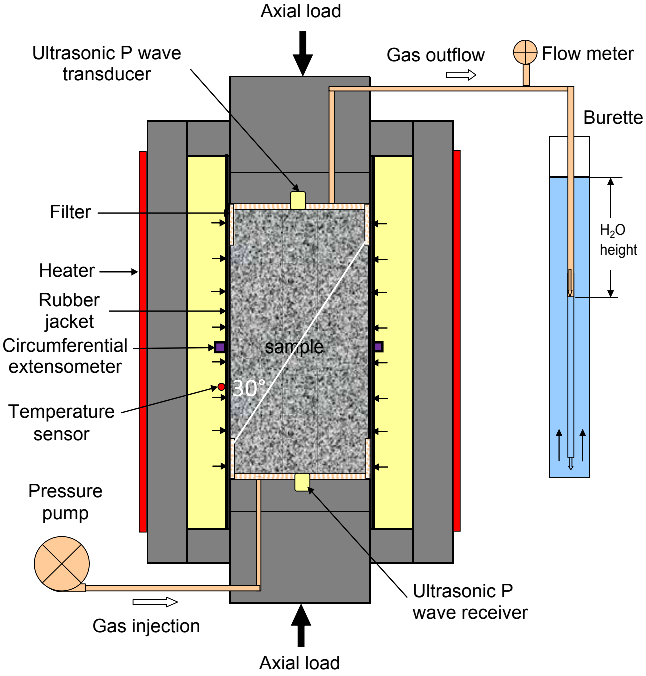

Fig. 1. Schematic assembly of a sample in triaxial cell with measurements of deformation, gas permeability, and ultrasonic wave velocity.

The tests were divided into two groups comprising at least 10 samples each for examining the repeatability of the results. Table 1 gives the test conditions and major results. A common test procedure was carried out for three sequential loading stages:

(1) Hydrostatic precompaction up to 15 MPa (group I) and 20 MPa (group II) to improve the quality of the samples, which are equivalent to and even higher than the in situ lithostatic stresses of 12.5–16 MPa at the sampling positions (Armand et al., 2014);
(2) Deviatoric loading by axial compression at a rate of 10^{-6} s^{-1} and at a lateral confining stress increasing from 0.5 MPa up to 12 MPa to investigate the deviatoric stress–strain response, damage and permeability changes of the intact claystone; and
(3) Recompression along different loading paths that are expected in the EDZ to examine the post-failure behaviour of the fractured claystone.

4. Test results and interpretation

4.1. Hydrostatic precompaction

Some typical results of the precompaction up to 20 MPa are presented in Fig. 2 in terms of volumetric strain and gas permeability versus applied hydrostatic load and unload. The stress–strain (σ_{m}–ε_{v}) curves along loading path show that the volumetric compaction is nonlinearly related to the hydrostatic load in the initial stage and then follows a linear relation. The initial nonlinear compaction is mostly attributed to the closure of the sampling-induced microcracks that are mostly aligned with the bedding planes in the axial direction. This becomes apparent by comparing the local strains perpendicular ($\varepsilon_{\perp}$) and parallel ($\varepsilon_{/\!/}$) to the bedding planes, as shown in Fig. 3. The strain $\varepsilon_{\perp}$ is larger than $\varepsilon_{/\!/}$ indicating less resistance to compaction in the normal direction of the cracks. The subsequent linear compaction is due to the elastic closure of the cracks and the pores in the matrix. Additionally, the progressive compaction at constant load indicates the viscoplastic deformation of the inner pore structure.