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Characterization of the hydromechanical behavior of argillaceous rocks with effective gas permeability under deviatoric stress

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ABSTRACT

The realization of nuclear waste storage in the deep geological formation will change the hydromechanical properties of the host rocks around the man-made openings due to the stress redistribution during the excavation stage and the variation of the hydraulic conditions during the open drift stage and the closure stage. This paper mainly presents an experimental study on the evolution of effective gas permeability of Callovo–Oxfordient argillaceous rocks during dehydration and rehydration processes and its variation under loading and unloading conditions. The experimental results show that effective gas permeability increases with the diminution of degree of saturation, and the logarithm of effective gas permeability is in quasi linear relation to saturation for the degree of saturation less than 90%. But effective gas permeability is not sensitive to the deviatoric stress, even if the deviator exceeds the damage threshold. The method of mercury intrusion has also been used in studying the microstructure of argillaceous rocks.

1. Introduction

In order to demonstrate the feasibility of radioactive waste repository in a deep argillite formation, Andra started in 2000 to build an underground research laboratory (URL) in Eastern France. The host formation consists of Callovo–Oxfordian argillaceous rocks, and is approximately 500 m deep and 130 m thick (Andra Dossier, 2005). Very low permeability and relatively homogenous mechanical characteristics are the most important properties of the investigated rock so that this formation has been chosen as a potential host rock of nuclear waste repository.

The creation of EDZ (excavation damaged zone) and its evolution over time due to the realization of the underground nuclear waste storage have been investigated numerically and experimentally through a large number of projects. The impact of ventilation on its evolution is one of the important issues because of swelling and shrinking properties of the argillites. The amplitude of shrinking could reach up to 1% while the argillaceous rocks desaturated down to 40%. Cracking and re-opening of micro-fractures were observed in the laboratory and in field, where the argillaceous rocks were undergone a resaturation and desaturation cycles (Billiotte et al., 2008; Valès, 2008; Ramambasoa, 2001). The kinetic evolution is controlled by the water and gas permeability of the rock, and also is a coupled hydro-mechanical problem.

This paper is devoted to the characterization of permeability of argillaceous rocks during resaturation or desaturation cycles. Effective gas permeability measurements on six twin samples, cored from the EDZ of the mains access shaft of the URL, have been performed. The effects of desaturation and resaturation cycles as well as the deviatoric stress have been investigated.

In addition, three core samples cored from 0.7 m, 4 m and 12 m to the shaft wall at 467 m depth behind the excavation face were tested. This paper presents the results of the variation of effective gas permeability on these samples, and their comparison with in situ water permeability measurements performed in boreholes. The comparison leads to enhancing the confidence on the extension and amplitude of EDZ (excavation damaged zone) induced by the shaft sinking.

This paper starts with the physical properties of the argillaceous rocks. The experimental set-up of gas permeability measurement and the experimental process are then presented. The experimental results of effective gas permeability under different conditions are presented and compared with the in situ water permeability measurements. The relationship between effective gas permeability and degree saturation is proposed. Its validity is discussed. The relation between the mechanical damage and effective gas permeability will be discussed in the last part.

2. Material

The Callovo–Oxfordian argillaceous rocks contain an average of 40–45% clay minerals (illite, regular mixed layer R1 illite–smectite, chlorite and kaolinite in the lower part, illite and irregular mixed layer R0 illite–smectite in the upper part), 22–37% of carbonates, 25–30% of quartz, and

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Table 1
Physical properties of the samples at initial state.

Sample	Location (m)	Length (mm)	Diameter (mm)	Weight (g)	w (%)	n_T (%)	Sr (%)
EST20548-1	4.15	65.40	39.90	199.92	5.28	14.6	84
EST20548-2	4.19	53.42	39.92	163.78	5.28	14.5	85
EST20548-3	4.23	60.04	39.92	186.64	5.18	13.8	89
EST20548-4	4.28	62.80	39.98	192.64	5.49	14.8	86
EST20548-5	4.34	62.82	39.98	193.03	5.53	14.3	87
EST20548-6	4.39	59.32	39.92	182.37	5.30	14.2	87
EST20512-1	0.45	31.74	39.98	96.83	5.88	15.6	86
EST20567-1	12.45	46.20	39.94	139.12	6.94	17.3	90

less than 5% of other materials (for example, pyrite). The initial water content generally varies between 5% and 9% and the water presents principally in the matrix of clay (ANDRA Dossier, 2005).

8 cylindrical samples of 40 mm in diameter and 30 to 70 mm in length have been prepared from 3 cores, which were taken from the different distances (0.45 m, 4 m, 12.45 m) to the main shaft wall of the URL. The cooling and evacuation of material during the coring of the samples have been assured by the compressed air at 0.2 MPa.

The physical properties of these samples at initial state are given in Table 1. The six twin samples from about 4 m to the main shaft wall present similar characteristics: water content is about 5.3%; total porosity is about 14.3%, and the grain density is 2.72 g/cm^3. The water contents of the other two samples at the distance of 0.45 m and 12.45 m to the main shaft wall are respectively 5.88% and 6.94%; the total porosities are respectively 16% and 17%. The difference of water content between these samples can be explained by the EDZ: the sample EST20567-1 far away from the main shaft wall of the URL is less affected by the excavation and the sample is relatively intact. It is noticed that the samples from 4 m to the main shaft were prepared 12 months later than the other two samples. Their drier states (w = 5.3%) may be related with the conservation situation of the core plug.

In order to characterize the hydromechanical damage, these 8 samples have been tested in a gas permeability equipment under different conditions (degree of saturation, deviatoric stress).

3. Experimental method and experimental process

3.1. Transient method

There usually exist two methods to measure the permeability: the steady state method and the transient method. The steady state method is very precise and acceptable for permeability larger than 10^{-19} m^2. It needs a precise flow meter in order to measure the very slow flux and a long time for assessing steady state flow in the case of permeability around 10^{-19} m^2. However, transient pulse techniques (Brace, 1968 and P.A. Hsieh et al., 1981 and Neuzil and Cooley, 1981) are usually used to determine low permeability, moreover it is less time consuming. This method has been chosen for determinating the permeability of argillaceous rocks. Instead of water, inert gas has been chosen as a flow medium, because it presents lower viscosity and it is not sensitive to the clayey matrix.

The principle of 'Pulse test' consists of an increment pressure ΔP_0 in one of two reservoirs connected with each end of a sample, which has a uniform initial pressureP_0. In considering the validity of some laws, for example, the mass conservation law, Darcy's law and ideal gas law, the mathematical model of gas pulse test can be expressed by Eq. (1). The initial and boundary conditions are described by Eqs. (2) and (3).

$$\frac{\partial}{\partial x}\left(k\frac{\rho}{\mu}\frac{\partial P}{\partial x}\right) = \beta n\rho\frac{\partial P}{\partial t} \tag{1}$$

where k is the effective gas permeability, ρ is the gas density, μ is the gas dynamic viscosity, β is the compressibility factor, n is the effective porosity that the medium fluid occupies.

$$\begin{aligned} &P(x,t=0) = P_0; \quad \text{for } 0 < x \le L \\ &P(x,t=0) = P_0 + \Delta P_0; \text{ for } x = 0 \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{\partial P}{\partial x} &= \frac{V_{up}\mu\beta}{kA}\left(\frac{\partial P}{\partial t}\right)_{x=0,t>0} = \frac{V_{up}\mu\beta}{kA}\frac{dP_{up}}{dt} \\ \frac{\partial P}{\partial x} &= \frac{V_{down}\mu\beta}{kA}\left(\frac{\partial P}{\partial t}\right)_{x=L,t>0} = \frac{V_{down}\mu\beta}{kA}\frac{dP_{down}}{dt} \end{aligned} \tag{3}$$

where V_{up} and V_{down} are respectively the volumes of the upstream and downstream reservoirs and A is the cross sectional area of the sample.

3.2. Experimental set-up

Based on the principle of 'pulse test' (Billiotte et al., 2008; Le Guen and Billiotte, 1993), an experimental equipment of gas permeability measurements has been designed and developed in the GIG/Geosciences laboratory.

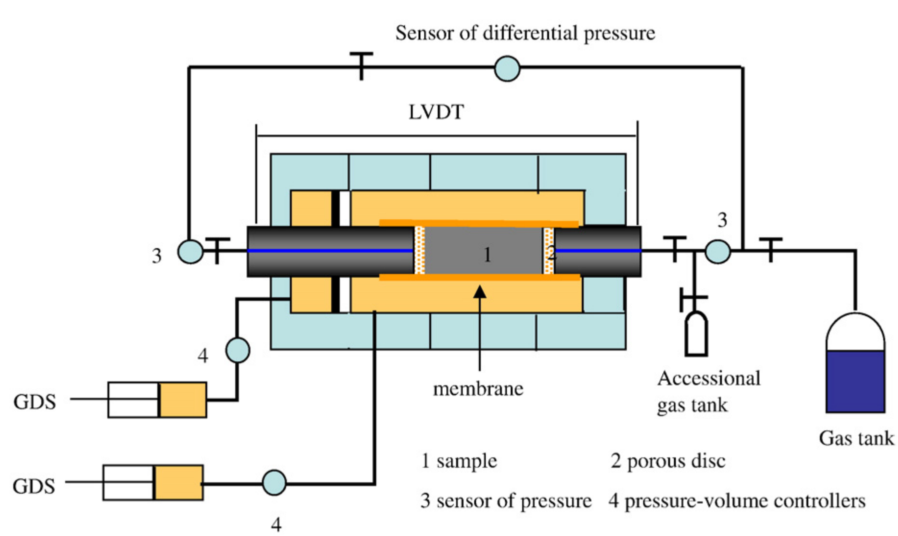

Fig. 1. Schematic of the gas permeability apparatus of GIG/Geosciences laboratory.