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Effects of temperature and thermally-induced microstructure change on hydraulic conductivity of Boom Clay

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ABSTRACT

Boom Clay is one of the potential host rocks for deep geological disposal of high-level radioactive nuclear waste in Belgium. In order to investigate the mechanism of hydraulic conductivity variation under complex thermo-mechanical coupling conditions and to better understand the thermo-hydro-mechanical (THM) coupling behaviour of Boom Clay, a series of permeability tests using temperature-controlled triaxial cell has been carried out on the Boom Clay samples taken from Belgian underground research laboratory (URL) HADES. Due to its sedimentary nature, Boom Clay presents across-anisotropy with respect to its sub-horizontal bedding plane. Direct measurements of the vertical (K_v) and horizontal (K_h) hydraulic conductivities show that the hydraulic conductivity at 80 °C is about 2.4 times larger than that at room temperature (23 °C), and the hydraulic conductivity variation with temperature is basically reversible during heating–cooling cycle. The anisotropic property of Boom Clay is studied by scanning electron microscope (SEM) tests, which highlight the transversely isotropic characteristics of intact Boom Clay. It is shown that the sub-horizontal bedding feature accounts for the horizontal permeability higher than the vertical one. The measured increment in hydraulic conductivity with temperature is lower than the calculated one when merely considering the changes in water kinematic viscosity and density with temperature. The nuclear magnetic resonance (NMR) tests have also been carried out to investigate the impact of microstructure variation on the THM properties of clay. The results show that heating under unconstrained boundary condition will produce larger size of pores and weaken the microstructure. The discrepancy between the hydraulic conductivity experimentally measured and predicted (considering water viscosity and density changes with temperature) can be attributed to the microstructural weakening effect on the thermal volume change behaviour of Boom Clay. Based on the experimental results, a hydraulic conductivity evolution model is proposed and then implemented in ABAQUS. Three-dimensional (3D) numerical simulation of the admissible thermal loading for argillaceous storage (ATLAS) III in situ heating test has been conducted subsequently, and the numerical results are in good agreement with field measurements.

1. Introduction

Deep geological disposal of high-level radioactive waste (HLW) in clay formations is one of the promising methods. Boom Clay is considered to be one of the potential host rocks for HLW disposal in Belgium because of its strong adsorption capacity, low permeability (10^{-12} m/s), self-sealing capacity and favourable creep properties (Neerdael and Boyazis, 1997; Bernier et al., 2004). Comprehensive investigations of the hydro-mechanical properties of this argillaceous rock have been carried out at the underground research laboratory (URL) HADES since 1980. Due to the heat emitted by the HLW, the temperature of the clay barrier is expected to be increased after the installation of waste canisters. The temperature changes

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would increase the hydraulic conductivity of Boom Clay and consequently compromise the favourable properties of clay formation as a natural barrier for migration of radionuclide. A better understanding of this issue is thus important for the repository performance and safety assessments.

The thermal effect on hydraulic conductivity of Boom Clay has been widely studied. Sultan (1997) observed that the hydraulic conductivity of Boom Clay was up to two times larger when the temperature changed from 35 °C to 60 °C. Delage et al. (2000) reported that the hydraulic conductivity of Boom Clay increased from 2.5×10^{-12} m/s to 6.2×10^{-12} m/s with temperature increasing from 20 °C to 90 °C. In order to assess the self-sealing capacity of damaged Boom Clay, Monfared et al. (2012) and Chen et al. (2014) investigated the thermal effect on hydraulic conductivity of Boom Clay pre-damaged by shearing and artificial fracture. They found that the shear band or artificial fracture does not significantly affect the permeability, because Boom Clay presents a good self-sealing capacity. Nevertheless, the results focussing on Boom Clay are still limited to enable a refined interpretation of the large-scale in situ PRACLAY heater test in Belgian URL HADES (Li et al., 2010).

A number of studies (Wemaere et al., 1997; Bastiaens and Demarche, 2003; Dehandschutter et al., 2004; Bastiaens et al., 2007; Piriyakul and Haegeman, 2009; Chen et al., 2011; Lima, 2011) indicate that Boom Clay presents anisotropic properties. Dehandschutter et al. (2005) observed bedding planes of fractured Boom Clay by scanning electron microscope (SEM) observations. Indeed, in the presence of sub-horizontal bedding planes, Boom Clay can be considered as a transversely isotropic geomaterial (Yu et al., 2014). The anisotropic property of permeability of Boom Clay has been investigated by in situ experiments (Bastiaens et al., 2006). For this, the anisotropic properties are further investigated by more laboratory experiments in this study.

In most above-mentioned studies, the increase in hydraulic conductivity with temperature has been considered due to the decrease in viscosity of fluid (Habibagahi, 1977; Cho et al., 1999; Delage et al., 2011). However, the changes of hydraulic conductivity with temperature are not only influenced by the changes of water properties, but also by the thermal effect on soil-water interaction at microstructural level (Towhata et al., 1993; Romero et al., 2001; Villar and Lloret, 2004). As the temperature increases, the thermal effects would alter clay fabric (Romero et al., 2001), produce larger voids between clay particles (Pusch and Güven, 1990; Pons et al., 1994; Thomas et al., 1994), change the effective flow cross-sectional area of porous channels (Ye et al., 2013, 2014), and degenerate the absorbed water into free water (Derjaguin et al., 1986). Consequently, there are different interpretations on the discrepancy of hydraulic conductivity between the test results and the predictions by considering water properties changing with temperature (Table 1). Towhata et al. (1993) analysed the influence of temperature on the permeability of MC clay and bentonite, and concluded that the increment of measured hydraulic conductivity with temperature was higher than the calculated one by using properties of free and pure water. They attributed this discrepancy to the degeneration of absorbed water into free water at elevated temperatures, which may result in easier seepage through the clay. On the other hand, Houston and Lin (1987) measured hydraulic conductivity values of illite, and Villar and Lloret (2004) conducted hydraulic conductivity test of bentonite at different temperatures. Their results showed that the increase in hydraulic conductivity due to temperature evolution was smaller than the prediction as per water viscosity change. They suggested that this may account for the soil densification by thermal consolidation, and the variation of hydraulic conductivity with temperature may depend on the type of material. Romero et al. (2001) gave similar results for unsaturated Boom Clay and attributed this discrepancy to the clay fabric alteration and porosity redistribution by thermo-chemical effects. Wan (2010) investigated the thermal effects on the microstructure of the GMZ01 bentonite using mercury intrusion porosimetry (MIP) technique. Results showed that, under confined conditions, the pore structure of the saturated GMZ01 bentonite changes slightly with temperature. However, it reveals that the thermal effect on microstructure of clay has not been fully understood to date, due to significant effect of microstructure on thermo-hydro-mechanical (THM) properties of clay. The nuclear magnetic resonance (NMR) technique is used to investigate the microstructure change behaviour of clay without disturbing the tested samples (Bird et al., 2005; Bayer et al., 2010).

This paper first presents the experimental results obtained using permeability tests considering heating–cooling cycle, as well as the SEM and NMR tests conducted on heated Boom Clay samples. These laboratory tests results help to understand the thermal effect on hydraulic conductivity. The anisotropy of hydraulic properties of Boom Clay as well as the importance of the thermally-induced microstructure change and its effect on the THM behaviour of Boom Clay is concerned. Next, based on the experimental results, a model for hydraulic conductivity of Boom Clay in relation to temperature is proposed and then implemented in ABAQUS through USDFLD subroutine. Finally, a three-dimensional (3D) numerical simulation of the admissible thermal loading for argillaceous storage (ATLAS) III in situ heating test is conducted, and the numerical results are compared with in situ measurements.

2. Materials and experimental investigations

2.1. Boom Clay samples

The Boom Clay samples are extracted at a depth of 223 m and at dozens of metres deep from the sidewall of connecting gallery of the URL HADES. Boom Clay is a dense plastic clay, with a total porosity of around 39% and water content of 24%–30%. The dominant fraction (around 60%) contains illite, smectite, illite-smectite mix layer and kaolinite. The non-clay mineral is mainly composed of quartz (25%), feldspar with a little pyrite, and calcite (Yu et al., 2012).

Table 1
Review of comparison of hydraulic conductivity values measured and predicted on the basis of water properties changing with temperature.

Source	Clay type	Temperature range (°C)	Test method	Test result	Reason of discrepancy
Towhata et al. (1993)	Bentonite and MC clay	20–90	Calculated from c_v measurements	Measured > predicted	Thermally-induced degeneration of absorbed water into free water
Houston and Lin (1987)	Illite	4–200	Calculated from c_v measurements	Measured < predicted	Soil densified by thermal consolidation
Villar and Lloret (2004)	Bentonite	20–80	Constant head permeability tests	Measured < predicted	Dependency on the type of material
Romero et al. (2001)	Unsaturated Boom Clay	22–80	Transient method	Measured < predicted	Thermally-induced clay fabric modification and porosity redistribution