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Hydro-mechanical behaviour of the Cobourg limestone

M.H.B. Nasseri[a,*], R.P. Young[a], X. Su[b], T.S. Nguyen[b], Z. Li[b]

[a] Department of Civil Engineering, University of Toronto, 35 St. George Street, Toronto, ON, Canada M5S 1A4
[b] Canadian Nuclear Safety Commission, Ottawa, Canada

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1. Introduction

Two initiatives for the deep geological disposal of radioactive wastes[1,2] are currently being proposed in Canada. The proposed repositories rely on both the surrounding host rock and engineered barriers to contain and isolate wastes from the biosphere for hundreds of thousands to millions of years. The success of both projects depends largely on the long-term performance of these barriers. The Cobourg limestone of the Michigan Basin is currently considered as one potential host formation for geological disposal. The understanding of the hydro-mechanical behaviour of such a host rock is one of the essential requirements for the assessment of its performance as a barrier against radionuclide migration. The excavation of galleries and shafts of a deep geological repository (DGR) can induce damage in the surrounding rock. The excavation damage zone (EDZ) has higher permeability and reduced strength compared to the undisturbed rock and those factors must be considered in the design and safety assessment of the DGR.

The behaviour of an EDZ can be characterized by several approaches. Field investigations with packer testing have been applied to characterize the permeability of EDZ around tunnel sidewalls[3]. Laboratory experiments on seismic and mechanical properties were reported by[4] to evaluate the onset of dilatancy cracking of a clay rock. Other investigation methods such as seismic borehole measurements, borehole video recording, and core mapping were conducted[5,6] to compare the size of an EDZ around an excavated drift that was determined by deformation modulus and gas permeability. It was found that the latter (i.e. determined by gas permeability) gave better characterization of the EDZ extent, which is in average two times of the depth of the EDZ determined by the former approach (i.e. determined by deformation modulus). A comprehensive review can be found in[7] with respect to relevant processes, associated factors, and modelling and testing techniques on permeability of EDZs in various rock types.

The formation of an EDZ can be triggered by elastoplastic dilatancy, stress unloading, micro- and macro-cracking under loading, blast or desiccation.[8,9] The shape and extent of an EDZ is site-specific and can be correlated with the size of the opening, rock type and its mechanical property and anisotropy, and in situ stresses, among others. Strong local nonhomogeneity in an EDZ has been observed by several studies.[10,11] Permeability increase in an EDZ is caused by damage to the rock in the EDZ and the permeability of an EDZ will increase significantly near the excavation surface and decrease to the level of intact rock with distance away from the excavation surface, which agrees with the declining trend of porosity away from the shaft wall.[6,12] Some recent studies have been focused on gas permeation in damaged rocks[5,6,13] which was shown the gas permeability is a bit higher than water permeability due to the so called Klinkenberg effect.[6] The largest increase in permeability of an EDZ in indurated clay rock has been reported to be 6 orders of magnitude higher than that of intact rock[7] while an increase in permeability of an EDZ between 2 and 4 orders of magnitude higher than that of intact rocks has also been reported for various rocks measured either from site investigations or laboratory experiments.[4,5,13] However, permeability evolution with rock damage is rarely investigated and needs further investigations.

Permeability healing has been observed in various rocks in the field studies. Clay rocks were found to have the capacity to self-seal in contact with water after continued permeation for two years, resulting in a reduction of permeability by 2 orders of magnitude.[3,11] Permeations of gas and water through a cracked clay rock has been compared.[15] They noticed a significant and rapid reduction in permeability of the EDZ to the level of sound rock when it is permeated with water,

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[*] Corresponding author.
E-mail address: nasseri@ecf.utoronto.ca (M.H.B. Nasseri).

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which is attributed by swelling of clay minerals. This behaviour has also been observed by[14] when a fractured clay rock was permeated with humidified gas. Swelling of clay rock even contributes to the enhanced chemo-osmosis phenomenon as reported by.[16] A time-dependent permeability reduction and thus crack closure in Opalinus clay at constant pressure was found by[17] indicating the effect of viscous behaviours of rocks on the self-healing of fractures and on permeability evolution as recently considered in the numerical modelling studies.[18–20] Long-term observation of a drift in granite in Japan revealed a gradual reduction in permeability of the EDZ,[21] which was attributed to the poroelastic response of the aquifer due to extra compaction of solid skeleton under depressurization effect caused by excavation.

In this study, the authors conducted experimental research in order to confirm the hydro-mechanical behaviour of the Cobourg limestone under undamaged and damaged conditions. The experimental program consists of triaxial tests with increasing stress levels up to failure and with a controlled loading rate prior to and after failure. During the tests, permeability and seismic wave velocities were measured at different extent of damages in the rock for six specimens cored parallel and perpendicular to the bedding plane. This paper summarizes the testing equipment, experimental methodology and results. Interpretative modelling of the experimental results is discussed in another paper.

2. Description of experiments

2.1. Description of samples and testing equipment

The Cobourg limestone is a mottled light to dark grey, very fine- to coarse-grained, very hard, fossiliferous argillaceous limestone and is characterized by a nodular fabric and bioturbated bedding surfaces with minor intra-formational variation.[22] The block samples for the experiment were collected at St. Mary's quarry, around 55 km northeast of Toronto. The cylindrical testing specimens were cored parallel and perpendicular to the bedding plane in the laboratory. Porosity and density of the limestone were measured according to the ISRM standard procedure.[23] The specimens have a nominal diameter of 50.5 mm and length of 125 mm. Table 1 shows the physical properties measured for the Cobourg limestone.

The experiment was performed in the geophysical imaging cell (GIC) as shown in Fig. 1 at the Rock Fracture Dynamics Facility (RFDF) at the University of Toronto. The cell was equipped with ultrasonic-wave velocity stacks oriented along three orthogonal axes of X, Y and Z, enabling us to measure the evolution of compressional and shear wave velocities as a function of differential stresses. During the experiment, in addition to the axial deformational measuring unit of the Mechanical Testing Systems (MTS), two separate Linear Variable Differential Transformers (LVDTs) close to the specimen outside the cell (integrated part of the GIC) were also used to measure axial deformation of the specimen. The diametral strain of the specimen was measured with an in-built cantilever system within the GIC.

Table 1
Physical properties of the Cobourg limestone measured at the RFDF.

Specimen number	Length (cm)	Diameter (cm)	Porosity (%)	Dry density (g/cm^3)	Density at saturation (g/cm^3)
CLV-1-T	12.50	5.04	0.82	2.33	2.34
CLV-3-T	12.50	5.04	1.26	2.31	2.32
CLV-5-U	12.50	5.04	0.83	2.32	2.33
Average			0.97	2.32	2.33
Standard deviation			0.25	0.01	0.01
CLH-1-T	12.50	5.04	0.85	2.33	2.34
CLH-1-U	12.50	5.04	0.74	2.33	2.34
CLH-2-T	12.50	5.04	0.95	2.33	2.34
CLH-2-U	12.50	5.04	0.90	2.32	2.33
CLH-3-T	12.50	5.04	0.93	2.32	2.33
CLH-3-U	12.50	5.04	1.09	2.32	2.33
Average			0.91	2.33	2.34
Standard deviation			0.12	0.01	0.00

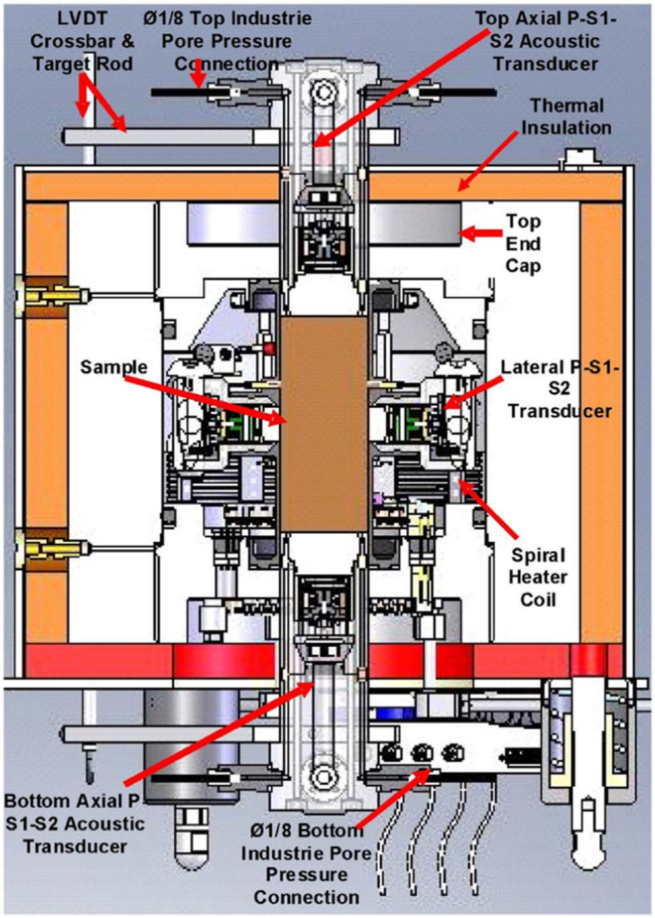

Fig. 1. Internal view of the geophysical imaging cell with rock specimen as well as the confining rubber and the X and Y and Z direction velocity stacks, (sketch is from former Ergotech and presently known as LEA- Lomobos Associates Ltd.).

2.2. Description of experimental method

Triaxial tests were performed at a room temperature of about 25 °C to measure the mechanical properties of the Cobourg limestone with permeability measurement at certain damage of the rock. The axial loading rate was controlled at a strain rate of 1.6×10^{-6} both pre- and post-failure. The permeability of the specimens was measured with the pulse decay method.[24] The servo-controlled load was kept on hold during the permeability measurement. A servo-control Quizix pump system (two pumps under independent constant control mode) was used to regulate the top and bottom pore pressures and to generate hydraulic pulses for permeability measurements under targeted axial stress levels up to the post-failure region. Prior to the permeability measurement, the upstream and downstream storage factors of the testing cell were evaluated using a steel sample of same size as that of the rock specimen as outlined by.[25] During the experiment, a 5 MPa confining pressure was applied and maintained, and a 3 MPa pore pressure (back pressure) was then applied to eliminate possible air in the system. The pore pressure decay at one end of the sample was then measured by introducing an additional 1 MPa hydraulic pulse. The pressure gradient decays exponentially to zero, and the pressure P_1 in reservoir 1 is given by Eq. (1):

$$(P_1 - P_f) = \Delta P\,[V_2/V_1) + V_2]_e^{-\alpha t} \tag{1}$$