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Influence of temperature on the hydro-mechanical behavior of Boom Clay

Hongdan Yu[a,*], Weizhong Chen[a,b,**], Zhe Gong[c], Yongshang Ma[a], Guangjing Chen[d], Xiangling Li[d]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, China
[b] Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan, China
[c] Wuhan Municipal Engineering Design and Research Institute, Wuhan, Hubei, China
[d] Euridice, SCK·CEN, Belgian Nuclear Research Centre, Mol, Belgium

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ABSTRACT

The purpose of this study is to identify common properties, as well as specific features of Boom Clay with regard to its response to thermo-hydro-mechanical (THM) loading through laboratory experiments, particularly at temperatures significant for radioactive waste disposal. Triaxial shearing tests at various temperatures and various effective confining pressures were performed on Boom Clay samples under undrained conditions. Test results clearly show that under the same hydro-mechanical conditions, an increase in temperature can cause a decrease of shear strength of Boom Clay. This weakening in shear strength was further interpreted as the reduction in cohesion and elastic modulus, and also the pore pressure build-up due to temperature elevation. However, the temperature effect on the friction angle is not clear. The results obtained confirm the effect of the overconsolidation ratio (OCR) on the thermal volume changes (contraction or dilation). The laboratory test results presented here give additional information to gain more insight into the thermal influence of heat emitting wastes on the behavior of clay, to validate and calibrate models.

1. Introduction

Radioactive waste must be managed and disposed of in ways that can well protect people and environment, now and in the future. Although several methods for disposing of radioactive wastes are being investigated, disposal in deep geological formation is at present the most appropriate means for isolating such wastes permanently from the human environment. The rock near to the waste is exposed to an elevated temperature as a side effect of radioactive decay and suffer changes in their hydraulic and mechanical properties. The influence of this thermal load is particularly important since the early transient THM perturbation might be the most severe impact on the repository system on a large spatial scale and in a relatively short period of time. For this reason, an accurate assessment of the coupling of thermal, hydraulic and mechanical processes of the host rock is an essential item for the safety of underground nuclear waste disposals.

In Belgium, the Boom Clay is considered as a potential host formation for the disposal of high-level radioactive waste owing to its various favorable properties, such as extremely low permeability, strong sorption capacity for many radionuclides, low but sufficient heat conductance, as well as its favorable self-sealing capacity. A large investigation program has been running since more than 30 years to characterize the Boom Clay formation, and numerous Boom Clay samples in the form of blocks or cores were taken and served for the different campaigns of laboratory tests. There are a number of laboratory results concerning the hydro-mechanical behavior of Boom Clay under a constant temperature field.[1–15] In comparison, the information on Boom Clay hydro-mechanical response to heating under controlled small-scale laboratory condition is still limited.[16–28]

In this paper, an experimental study intended to identify the effect of temperature on the hydro-mechanical behavior of Boom Clay is presented. This laboratory test program consisted of 15 series of CU (isotropically consolidated, undrained with pore water pressure measurements) tests at various temperatures (22, 40, 60, 80 °C) and confining pressures (2.5, 3.7, 4.7 MPa). Tests were carried out in a temperature-controlled compression cell able to sustain high pressures. Basic measurements are presented and commented on. In this study, maximum temperature has been limited to 80 °C, so that no appreciable phase and chemical change can occur.

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* Corresponding author.
** Corresponding author at: State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, China.
E-mail addresses: yuhd_1013@163.com (H. Yu), wzchen@whrsm.ac.cn (W. Chen).

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Table 1
Summary of the tests.

Test	ρ (g/cm^3)	w (%)	e_0	σ_c (MPa)	p_w (MPa)	T (°C)	Core information
HM$_{47222}$	2.01	24.0	0.697	4.7	1.2	22	2007/2, KERN 7, 25–65 cm
THM $_{47401}$	2.01	23.5	0.683			40	2006-S 4B
THM $_{47402}$	2.01	23.5	0.683			40	2006-S 4B
THM $_{47602}$	2.04	24.3	0.673			60	R76–77 16B 16.00–16.35
THM $_{47801}$	2.01	23.5	0.683			80	2006-S 4B
HM $_{37221}$	2.03	23.8	0.677	3.7	1.2	22	2007/2, KERN 6, 5–50 cm
THM $_{37401}$	2.04	24.2	0.671			40	R76–77 15B 14.65–15.15
THM $_{37402}$	2.00	23.5	0.693			40	R76–77 16 A 15,35–16,00
THM $_{37601}$	2.03	24.0	0.675			60	KERN 18 A 0–35
THM $_{37801}$	2.03	23.8	0.668			80	R74–75 14B 14.35–13.80
THM $_{37802}$	2.04	23.5	0.665			80	R76–77 14B 13,80–14,35
HM $_{25221}$	2.04	24.7	0.677	2.5	1.0	22	2006–5 6b
HM $_{25222}$	2.04	24.7	0.677			22	2006–5 6b
THM $_{27601}$	2.01	23.5	0.683	2.7	1.2	60	R70–71 2012 15.40–16.10
THM $_{27801}$	2.01	23.5	0.683			80	R70–71 2012 15.40–16.10

Note: ρ is density, w is water content, e_0 is the void ratio, σ_c is isotropic stress, p_w is back pressure, T is the temperature at which the sample is sheared. Synthetic Boom Clay water was used during the sample saturation.

2. Experimental testing

2.1. Soil tested

Tests were performed on Boom Clay samples, extracted at a depth of 223 m from the underground research laboratory HADES in Mol (Belgium). Boom Clay is a stiff clay, with a plasticity index of about 50%, a natural porosity around 40% and a water content comprised between 24% and 30%.[20] It is generally agreed that the clay fraction of Boom Clay is about 60% and mainly composed of illite, smectite, and kaolinite. Chlorite, chlorite-smectite mixed-layer and glauconite are found in small amounts.[11] Less unanimity exists about the contribution of illite-smectite mixed-layer.[29] The non-clay fraction is mainly composed of quartz and feldspar and the small content of pyrite, carbonates, and calcite. The Boom Clay samples were trimmed with the axis perpendicular to bedding. To do so, the original clay cores were machined on a lathe to obtain a sample with 38 mm diameter and 76 mm length. This manual procedure was chosen in order to limit crack formation and propagation. Table 1 gathers the basic conditions of all the tests, in which some petrophysical parameters (density, water content, void ratio, saturation degree, and core information) and load conditions (confining pressure, back pressure, and the temperature at which the samples were sheared) are included.

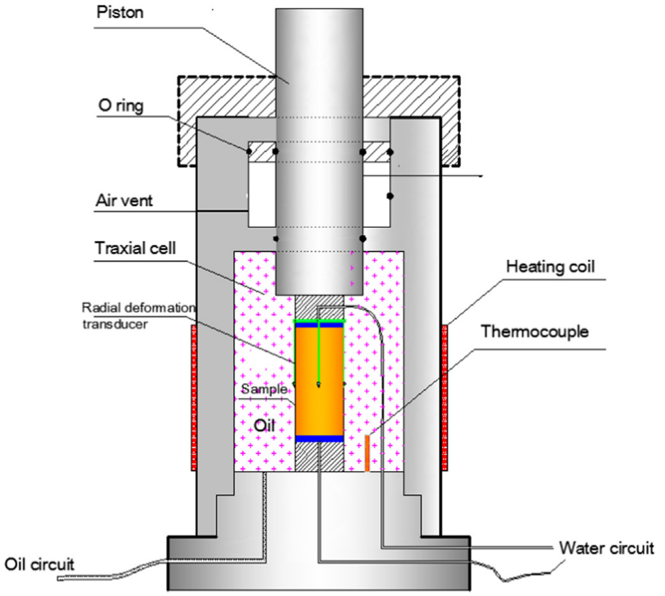

Fig. 1. Testing systems for the tests.

2.2. Experimental setup and test procedures

Tests were carried out in a triaxial cell (Fig. 1) designed to support certain pressures and temperatures (up to 10 MPa and 100 °C, respectively). The axial force was applied through a ball-screw control system. The load applied to the specimen was measured through an external load transducer. This kind of transducer is not sensitive to temperature and confining pressure changes in the cell, but may be sensitive to the friction of the loading ram through the top of the triaxial cell. This latter influence has been calibrated before the tests. The confining pressure and the back pressure were regulated by servo control systems. A pore pressure (4 ± 0.05 MPa) circuit regulated by large volume accumulators, allowed water to be funneled inside the sample through porous stone located at the upper and lower end caps. A heating coil was placed on the outer wall of the cell, and the temperature was controlled by a thermocouple put inside the cell in the confining oil. The volume changes of the sample were monitored by using both axial and radial deformation transducer. This equipment was installed in a temperature controlled room at 22 ± 0.5 °C.

Eighteen tests were performed on specimens of Boom Clay trimmed from the cores. The axis of the specimens is perpendicular to the bedding. Only 15 representative tests are discussed herein. The low permeability makes the mechanical behavior of Boom Clay a complex one. The tests are time-consuming as the test procedures have to carefully take-account of the specimen saturation, the temperature increasing and good control of the axial stress, confining pressure and pore water pressure (Fig. 2). To restore the in situ states of Boom Clay as much as possible, the isotropic stress of each sample was first increased to 2.5 MPa prior to any contact with water. This procedure reduced the swelling and thus the related microstructure changes.[6,7,30] Specimen saturation was achieved by increasing pore water pressure at the two ends (top and bottom) of the specimen. In detail, the soil sample was saturated by synthetic water with ionic composition similar to the in-situ pore water under the in situ mean effective stress of 2.5 MPa (except the samples THM$_{25221}$, THM$_{25222}$, THM$_{27601}$, and THM$_{27801}$, which were saturated under the mean effective stress of 1.5 MPa because of the low confined pressure). During the saturation stage, the isotropic stress and the back pressure were increased step-by-step by keeping the constant mean effective stress of 2.5 MPa, until a back pressure of 1.2 MPa. The loading rates for both isotropic stress and back pressure (as indicated in Fig. 2) were considered to be slow enough to ensure the complete drainage during loading. Then, the specimens were consolidated to a target mean effective stress under the