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BEHAVIOUR OF AN ENGINEERED CLAY BARRIER FOR A NUCLEAR WASTE ISOLATION SYSTEM

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1 INTRODUCTION

In a few years, safe and definitive solutions should be ready to manage large quantities of high-level radioactive waste. Deep geological repository involving a multi-barrier system constitutes one of the most promising options to isolate such waste from the human environment. In order to provide reasonable assurance of the waste isolation efficiency, it is essential to understand the behaviour of the confining geomaterials under a variety of environmental conditions, such as variations in temperature and humidity. To this end, results from a near-to-real scale experiment (the FEBEX in-situ test[1]) were studied by means of a thermo-hydro-mechanical (THM) finite element approach including a consistent thermo-plastic constitutive model for unsaturated soils.

2 CONSTITUTIVE MODEL

The behaviour of the buffer material (made of FEBEX bentonite) and the surrounding host rock (granite) involves many complex and interconnected THM phenomena. To carry out the numerical simulations, the ACMEG-TS elasto-thermoplastic constitutive model for unsaturated soils[2] has been implemented in the finite element code LAGAMINE[3]. Materials are considered as tri-phase non-isothermal medium. Phase changes of water (evaporation-condensation) and latent heat transfer are considered. The mechanical irreversibilities may be induced by stress-strain, suction or temperature loadings. The model uses the generalized effective stress, the temperature and the suction as state variables to fully describe the THM constitutive behaviour of the materials within an elasto-plastic framework. The elastic part of the deformation is due to the effective stress and temperature variations through thermo-elasticity. The plastic mechanism of the material is induced by two coupled hardening processes[4]: an isotropic and a deviatoric mechanisms affected by the temperature and suction levels through the evolution of the preconsolidation pressure (Figure 1a,b). In terms of water retention response, desaturation is also a yielding phenomenon. Hysteresis in water retention behaviour is modelled as a plastic process through two interconnected yield limits that are modified by the change of soil density and temperature (Figure 1c).

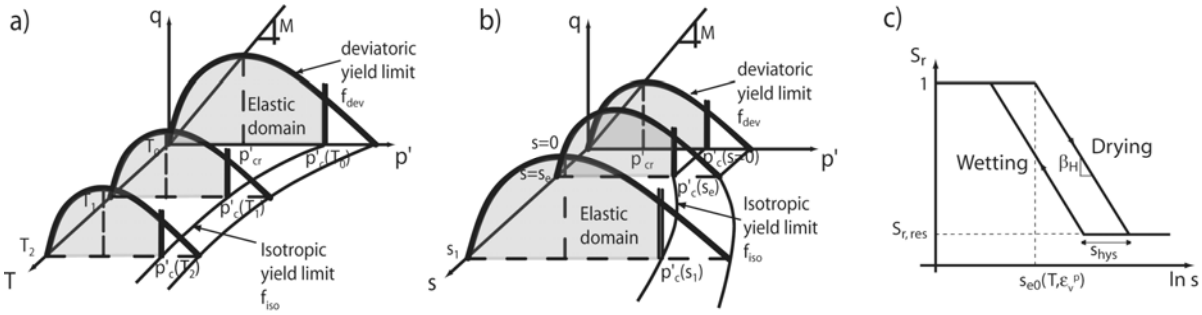

Figure 1. Effect of (a) temperature and (b) suction on the shape of coupled mechanical yield limits. (c) Schematic representation of water retention curve modelling.

The thermal and hydraulic diffusions in FEBEX bentonite give rise to interconnected phenomena. The water and air permeability are affected by the dry density, the temperature and the degree of saturation while the thermal diffusion depends on the quantities of each phases in the materials. The parameters governing the thermal and hydraulic diffusion in FEBEX bentonite are directly established from a literature synthesis while the material parameters of the ACMEG-TS model have been calibrated through a series of numerical simulations of oedometric tests on thermal, hydraulic and mechanical paths[2, 5].

3 FEATURES OF THE ANALYSIS

The problem is treated under axisymmetric conditions around the y-axis, which is the axis of the test drift. Consequently, gravity is not considered. The initial pore water pressure in the host granite is determined through a preliminary hydraulic calculation of the excavation phase, while a suction of 80 MPa is considered in bentonite. The initial water pressure in the concrete plug is assumed to be atmospheric pressure. The initial temperature is equal to 12°C in the entire modelled domain. An initial isotropic total stress of 28 MPa is imposed in the granite. The anisotropic stress state has not been considered in the simulation because of the axisymmetric formalism. In the bentonite, the external total stress is initially equal to zero, which corresponds to a generalized effective stress of 47.5 MPa (the initial product $S_r \times s$). The bentonite is assumed to be normally consolidated ($p'_{c0} = 4MPa$; $\gamma_s = 7$; $s = 80MPa$). The canister and the concrete plug are under zero stress. Finally, the air pressure has been fixed to atmospheric pressure in the entire unsaturated domain. The simulation has been performed on the first 700 days of operation (i.e. 2 years). The initial time of computation corresponds to the start of the heating (February 27th 1997).

4 RESULTS OF SIMULATIONS

Figure 2a,b reports the evolution of temperature with time in one section of the engineered barrier and in two boreholes in the rock mass. In section D1, the temperature field reaches a quasi-steady-state after 100 days. On the contrary, far from the heater (boreholes K1 and K2), the temperature continuously increases, even after two years of heating. The results of the simulation show a quit good agreement with in-situ measurements. In terms of relative humidity in the engineered barrier, Figure 2c,d displays the comparison between the measured and the computed values in two different sections of the engineered barrier. The simulation starts from a homogeneous relative humidity field equal to 60% (s = 80 MPa and T = 12°C), while the sensor measurements show an initial gradient of relative humidity in the considered section. However, after 200 days, the simulation and in-situ measurements exhibit very similar evolutions.

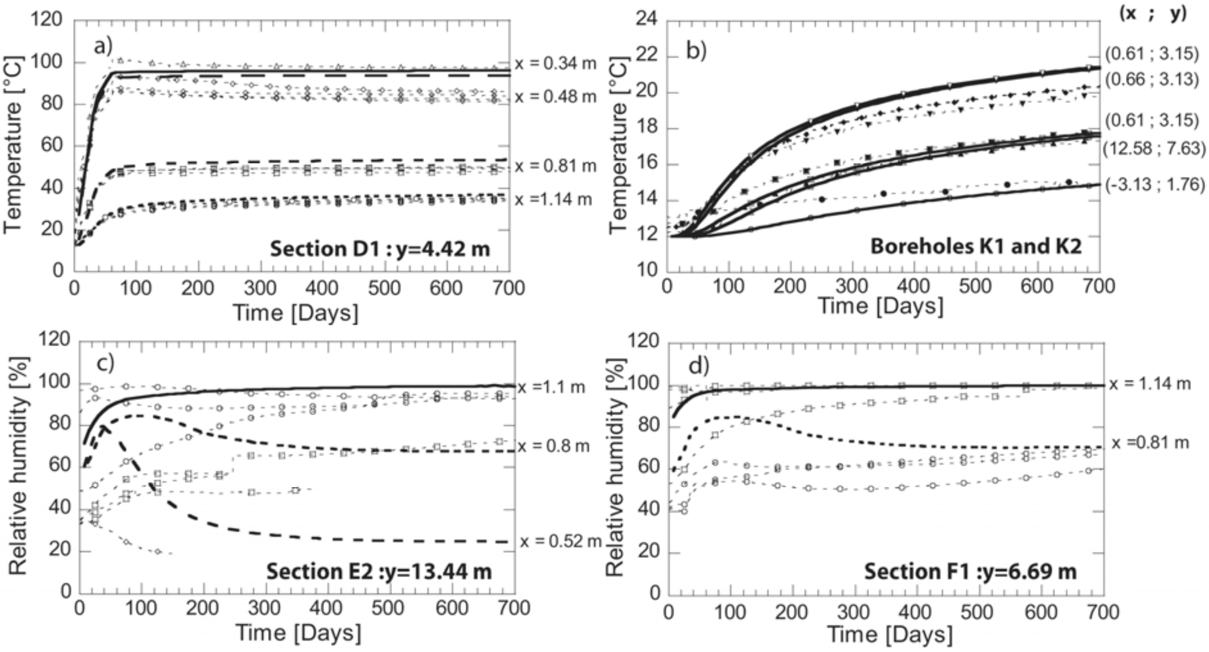

Figure 2. (a and b) Variation of temperature with time in two sections of the engineered barrier and in two boreholes in the host rock. (c and d) Variation of relative humidity with time in two sections of the engineered barrier. Comparison between numerical predictions (bold lines) and experimental measurements (thin dashed lines). y is the axial distance calculated from the bentonite/plug contact.

Figure 3a shows that the engineered barrier acts as a thermal buffer aimed at reducing the temperature in the host formation (no more than 40°C in comparison to 100°C in the canister). A quasi-steady-state thermal regime is rapidly reached in the bentonite (after less than 6 months). At the inner boundary, the temperature increase produces, via water evaporation, a drying of the clay. Consequently, the suction increases up to more than 200 MPa after 24 months, as shown in Figure 3b. It corresponds to a drop in the degree of saturation down to 0.6 (Figure 3c). At the outer boundary, the suction decreases and the degree of saturation increases. This is induced by two processes. (i) The higher water pressure of the granite than that in the buffer material implies a flow of water from granite to bentonite. This hydration process is the main contributor in resaturating the bentonite. (ii) Also, the vapour arising from the drying of the inner region diffuses through the engineered barrier and condensates in the cooler region.

In Figure 3d, the distribution of volumetric strain shows a contraction of the bentonite in the inner part while the outer part dilates. This is consistent with the hydraulic processes that occur in the engineered barrier. The temperature-induced drying produces shrinkage while the hydration of the outer part produces swelling. In addition, the bentonite is also prone to plastic processes such as thermal and hydraulic collapse. Comparison between the volumetric total strain (Figure 3d) and the volumetric plastic strain (Figure 3e) reveals that almost the entire contractile strain in the inner part is plastic. On the contrary, in the outer part, the low contractile plastic strain (+/- 3%) is compensated by high elastic swelling strain (+/- 6%). In terms of radial displacement, the contraction of the inner part, in addition to the dilatation of the outer part, produces an inward displacement of the engineered barrier (Figure 3f).

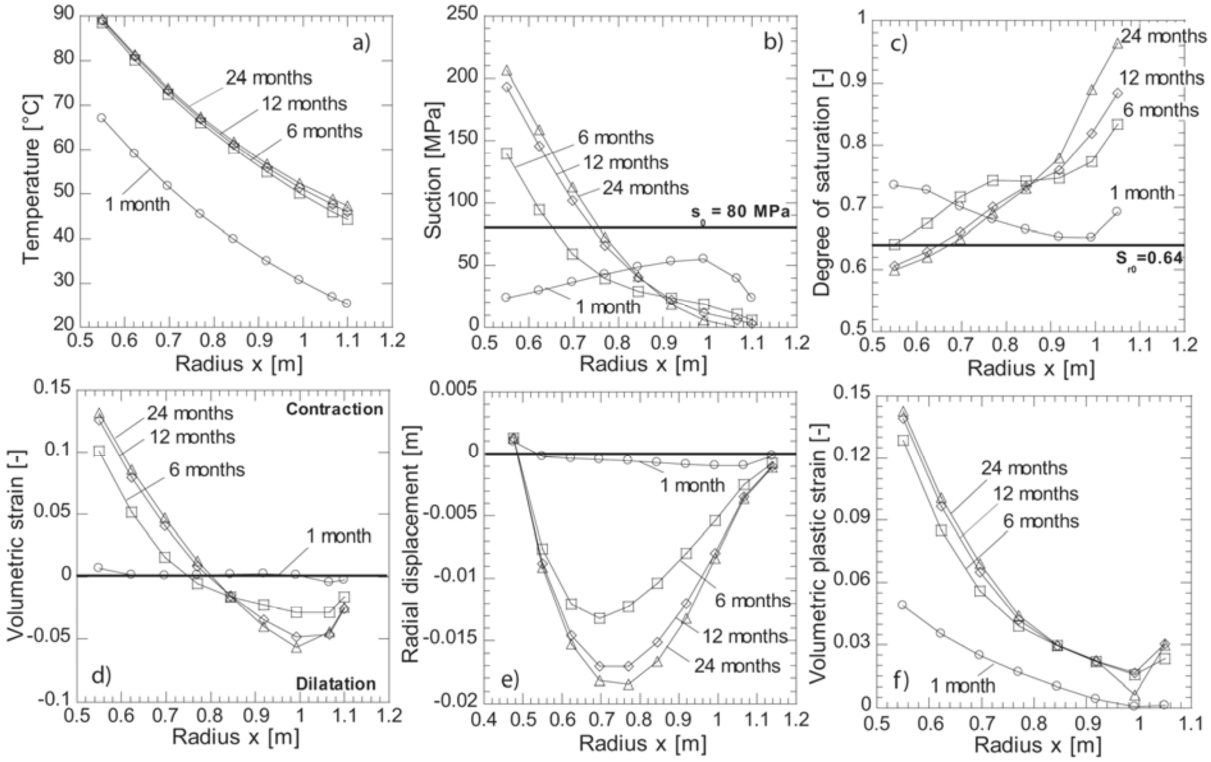

Figure 3. Evolution of the computed temperature (a), suction (b), degree of saturation (c), volumetric total strain (d), volumetric plastic strain (e) and radial displacement (f) along the mid-plane section of a heater at four different times.

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