Impact of Thermo-Hydro-Mechanical-Chemical Processes on the Safety of Underground Radioactive Waste Repositories
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Heating Pulse Tests under Constant Volume on Boom Clay. Experimental Results and Numerical Simulations

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1. INTRODUCTION

Boom clay is the subject of extensive research in Belgium dealing with all phenomena that may possibly affect the performance of this geological formation as potential radioactive waste repository. Specifically, thermal loads may play an important role on this low-permeability clay. To this aim, non-isothermal tests on intact borehole samples were carried out using an axi-symmetric heating cell. Heating and cooling paths under nearly constant volume and different target temperatures (maximum 85°C) were performed under controlled hydraulic boundary conditions. Selected test result are presented and afterwards calibrated and simulated using CODE_BRIGHT.

2. EXPERIMENTAL PROGRAMME

2.1. Boom clay

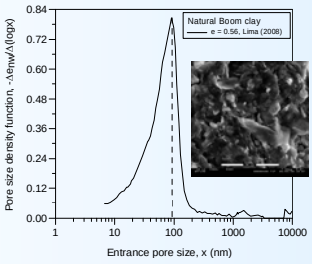
Horizontal borehole samples recovered at a depth of 230 m:

σ_v = 4.5 MPa u_w = 2.2 MPa p' = 2.4 MPa (K_0 = 0.8 to 1) OCR = 2.05 – 2.64 $p'_0 \approx$ 6 MPa

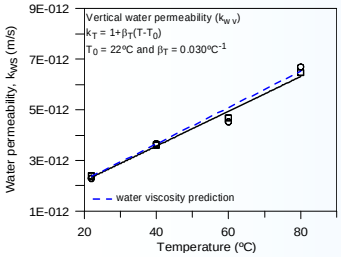
Density, ρ	1.99 to 2.05 Mg/m^3
Dry density, ρ_d	1.65 to 1.71 Mg/m^3
Gravimetric water content, w	21% to 25%
Initial total suction, Ψ	2 – 4 MPa
Density of soil solids, ρ_s	2.67 Mg/m^3
Void ratio, e	0.56 to 0.618
Porosity, n	0.358 to 0.382
Degree of saturation, Sr (*)	91 to 100 %
Liquid limit (using *SBCW*), w_L	56 %
Plasticity index, PI	27 %
Vertical water permeability (T=20ºC), k_{wv}	(2.4 to 3.1) x 10^{-12} m/s
Vertical water permeability (T=80ºC), k_{wv}	6.5 x 10^{-12} m/s
Horizontal water permeability (T=20ºC), k_{wh}	(5.7 to 7.4) x 10^{-12} m/s
Horizontal water permeability (T=80ºC), k_{wh}	1.26 x 10^{-11} m/s

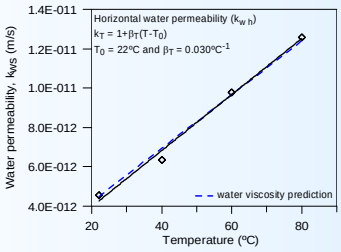
Synthetic Boom clay Water (*SBCW*) with similar composition to the natural water

(*) laboratory samples are not fully saturated due to some water content loss on storage

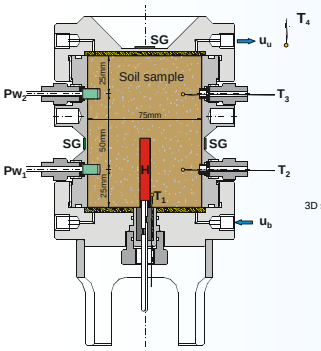


Water permeability at constant void ratio (temperature effects)





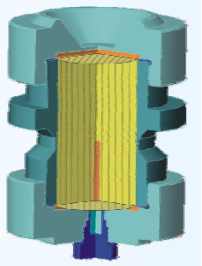
2.2. Heating cell and test protocols



adapted from Muñoz *et al.* (2009)

H - heater (length=40mm and diam.=6mm)
Pw_1 - pore water pressure bottom 25 mm
Pw_2 - pore water pressure top 75 mm
T_1 - temperature heater
T_2 - temperature bottom 25 mm
T_3 - temperature top 75 mm
T_4 - temperature water bath
SG - strain gauge
u_b - water inlet
u_u - water outlet

3D scheme for appreciation of bending planes position in the sample



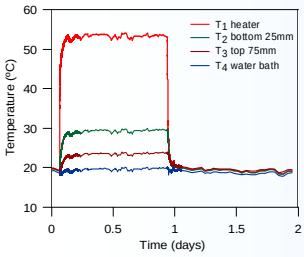
Test protocol

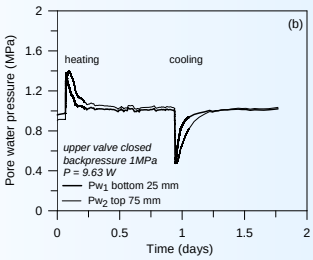
1) Hydration phase. Water pressure (bottom of the cell) was increased in steps (0.1, 0.5 and 1 MPa for final testing). The upper valve was kept open under atmospheric conditions.

2) Thermal phase. Throughout the heating and cooling paths, the bottom drainage was maintained open at a constant water pressure of 1 MPa using an automatic pressure / volume controller, while the upper valve was kept closed. This backpressure was important since it allowed measuring the pore pressure drop during the cooling phase while avoiding negative pressures (below atmospheric conditions).

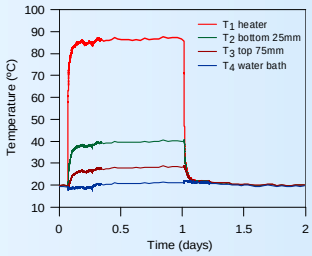
3. EXPERIMENTAL RESULTS

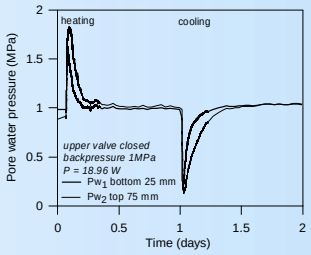
Thermal phase. Stage 3. Power supply: 10 W



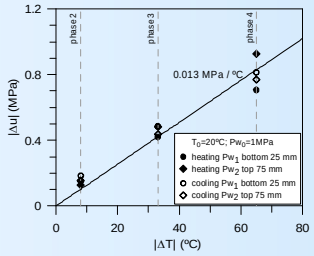


Thermal phase. Stage 4. Power supply: 19 W





Stages	Power supply (W)	Max. temp. T_1	Pw_1 (MPa) heat.	Pw_1 (MPa) cool.	Pw_2 (MPa) heat.	Pw_2 (MPa) cool.
2	2.78	28	1.15	0.81	1.13	0.85
3	9.63	53	1.38	0.48	1.39	0.48
4	19.0	85	1.69	0.17	1.83	0.13

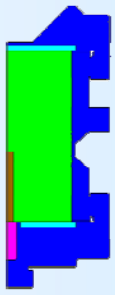


Some values:

- 0.06 MPa/°C for natural Boom clay based on Sultan (1997) data (Vardoulakis 2002)
- 0.005 MPa/°C for compacted Boom clay at S_{ro}=94% (Romero 1999)
- 0.01 to 0.05 MPa/°C for clay (Campanella & Mitchell 1968)

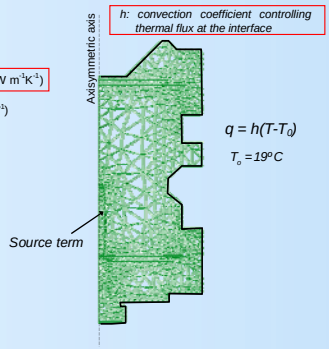
4. CALIBRATION AND NUMERICAL SIMULATIONS

Material parameters and boundary conditions

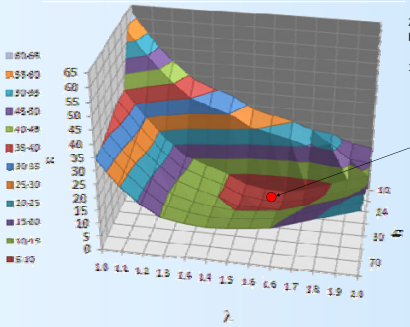


1. Soil (C_s = 874 J kg^{-1}K^{-1}; λ = 1.0 to 2.0 W m^{-1}K^{-1})
2. Stainless steel (C_s = 460 J kg^{-1}K^{-1}; λ = 45 W m^{-1}K^{-1})
3. Heater
4. Porous disk
5. Epoxy resin

heating phase	Power source (J s^{-1} m^{-3})
1	2.11x10^6
2	2.11x10^6
3	7.08x10^6
4	13.94x10^6



Calibration and simulations

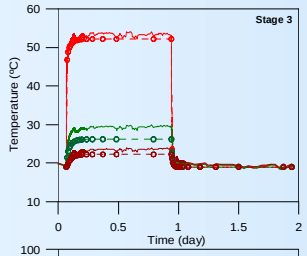


λ = 1.0 to 2.0 Wm^{-1}K^{-1} (interval of 0.1)
h = 10, 20, 24, 25, 30, 50, 70 and 100 Wm^{-2}K^{-1}

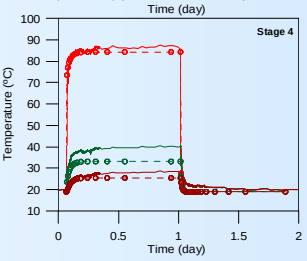
104 calculations were performed

λ = 1.6 Wm^{-1}K^{-1}
h = 24 Wm^{-2}K^{-1}

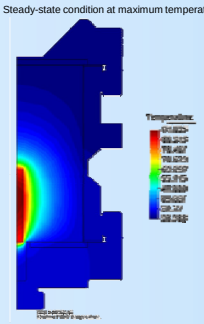
λ = 1.35 – 1.7 Wm^{-1}K^{-1}
(ATLAS and SAFIR2)



Test: T1, T2, T3
Simulation: T1 - heater; T2 - bottom 2.5cm; T3 - upper 7.5cm



Stage 4. Steady-state condition at maximum temperature



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