
On the thermal behaviour of Boom clay

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Abstract: When temperature is increased, the various phenomena that occur in a saturated natural potential host clay for nuclear waste disposal (Boom clay from SCK-CEN in Mol, Belgium) were experimentally investigated in a temperature controlled high stress triaxial cell. Firstly, the pore pressure build-up due to the difference in thermal dilation of both water and minerals was investigated through thermal consolidation tests. Interesting information was obtained about the dissipation of thermally induced pore pressure in Boom clay, based on the standard Terzaghi consolidation theory. Secondly, the volume change behaviour in drained conditions (i.e. under a very slow temperature increase) confirmed that the clay overconsolidation ratio (OCR) controlled the nature of the volume changes. Whereas overconsolidated soils use to dilate as any material when temperature is elevated, normally consolidated soils present a decrease in volume, which is less common. The principles of a coupled thermo-elasto-plastic model that was specifically developed to model this particular behaviour are finally presented. Obviously, it appears necessary to account in detail for these thermal phenomena in order to properly understand the response of the geological barrier in the near field once nuclear waste has been stored.

1 INTRODUCTION

Soils surrounding nuclear waste disposal are exposed to an elevated temperature during a long period of time and suffer from the thermal expansion of the soil solids and of the pore water. In conditions of fast heating and poor drainage, heating may give rise to i) the build-up of thermal excess pore pressures, ii) the corresponding reduction of the in-situ effective stress, and iii) the subsequent volume changes due to the dissipation of excess pore pressure. Obviously, thermal volume changes affect the hydraulic and mechanical properties of soils and they are to be considered in detail when designing nuclear waste disposals.

Particular attention has recently been paid to the thermomechanical behaviour of Boom clay, in relation with the underground laboratory of the Belgian Nuclear Research Center (SCK-CEN) in Mol, which is located in the Boom clay deposit. Investigations have been devoted to the understanding of the thermoconsolidation and further attention has also been paid to the investigation of the exact nature of the volume changes due to heating. It has been shown that overconsolidation ratio (OCR, i.e. the ratio between the in-situ stress and the yield stress) has a significant effect on the nature (expansion or contraction) of the thermal volume change. These aspects are described in this paper.

2 MATERIAL AND METHODS

Samples were extracted from a depth of 223 m in the Boom clay deposit (Declerck et al. 1983) in the underground facilities of SCK-CEN in Mol (Belgium). The thermo-mechanical behaviour of Boom clay has been experimentally studied by various authors (Baldi et al.

1988, 1991, Neerdael et al. 1992, De Bruyn and Thimus 1995, Bernier et al. 1995, Belanteur et al. 1997) in relation with nuclear waste disposal. 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%.

Tests were carried out in an isotropic compression cell (Figure 1) designed to support high pressures and temperatures (up to 60 MPa and 100°C respectively). An electrical heating band was placed on the outer wall of the cell, and the temperature was controlled by a thermocouple placed inside the cell. The accuracy of the temperature regulation system is $\pm 0.05^\circ\text{C}$. The isotropic stress was applied by a high pressure/volume GDS controller (60MPa), and the back pressure (up to 2 MPa) by a standard pressure/volume GDS controller. The main advantage of this system is its ability to monitor volume changes while applying pressures.

In standard isothermal triaxial tests carried out on saturated samples of soils, volume changes are measured by monitoring the transfer of pore water into or out a sample. This is no longer valid in non-isothermal conditions, because of the thermal dilation of water and solids. For this reason, a volume monitoring based on the transfer of confining water contained in the cell was adopted. A careful calibration was made either in terms of pressure or in terms of temperature by performing tests along various paths of pressure and temperature. Heating tests (between 20 and 100°C) were carried out on a blank metallic sample under 6 different values of confining pressure (1, 2, 3, 5, 10 and 12 MPa). Compression tests between 0 and 10 MPa were carried out under temperatures of 20, 80 and 100°C.

The accuracy of volume change measurements during heating tests are affected by the thermal expansion of the device. This also concerns the changes in the temperature gradients in the water located in the internal ducts connecting the pressure controllers (at the ambient temperature, i.e. 20°C) either to the base of the sample, or to the water cell (both at test temperature). In order to minimise this problem, the metal tubes connecting the cell to the pressure controllers were immersed in water baths maintained at 20°C (see Fig. 1). For low heating rates and slow movements of water during heating, the system imposes the 20°C temperature condition right at the outlet. Thereby the volume of the water located in the cell base, in which temperature is decreasing, is maintained constant.

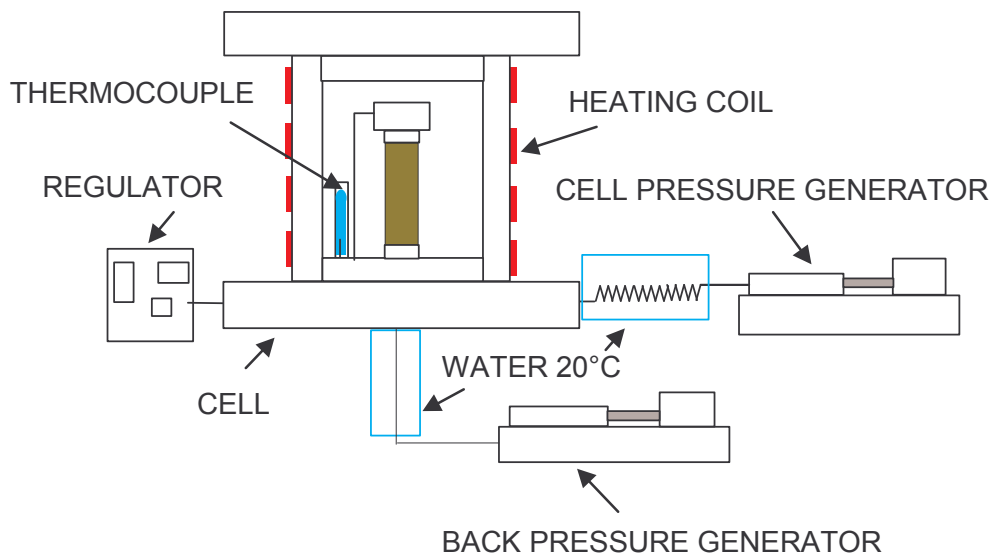


Figure 1. Thermal high pressure triaxial device

3. THERMAL CONSOLIDATION TESTS

A sample of natural Boom clay was saturated under a back pressure of 1 MPa and an isotropic effective stress of 30 kPa. Once saturated, the soil was isotropically consolidated in the temperature controlled laboratory (20°C) under an all round pressure of 4 MPa, and subsequently unloaded down to 2 MPa, leading to an overconsolidation ratio OCR = 2.

Thermal consolidation tests at different temperatures were carried out by applying 10°C temperature increments. Starting from 20°C, the temperature regulating system was switched on at the desired temperature (30°C in the first heating step), until stabilisation at the desired temperature was detected by the thermocouple placed in the water inside the confining cell (see Figure 1). The duration of the heating phase depends on the power of the heating system, on the mass and on the heat capacity of the system. It lasted approximately 1.5 hours. During the test, the 1 MPa back pressure was maintained using the GDS controller connected to the base of the sample, whereas the top connection was closed. So, the length of drainage was equal to the length of the sample. The test can be interpreted like a standard oedometer test, and two kinds of curves are obtained :

- a) curves giving the volume changes as a function of time, which are related to the rate of dissipation of excess pore pressures
- b) strain-temperature curves, obtained by considering all the final points once the stabilisation of volume change has been attained.

An expansion was observed in the tests carried out between 23 and 50°C whereas a contraction was observed at higher temperatures (50-60, 60-70, 70-80 and 80-95°C). The thermal contraction of the soil results in an expulsion of water similar to that occurring in standard consolidation. These tests will be considered in the following.

Figure 2 shows the thermal volume changes curves versus the logarithm of time of the tests at higher temperature. (50-60, 60-70, 70-80 and 80-95°C).

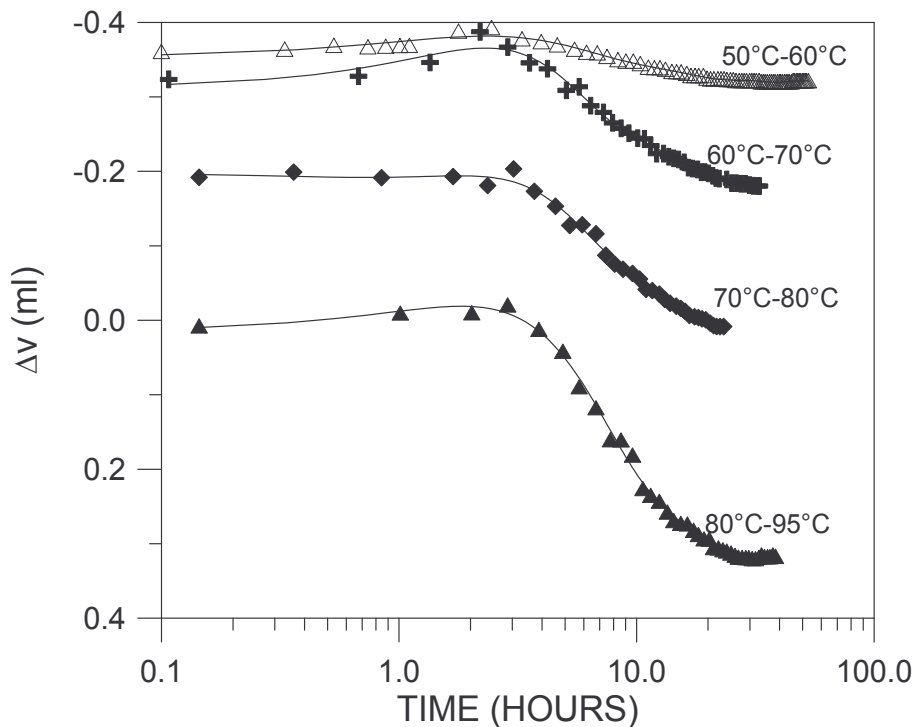


Figure 2 : Thermal consolidation curves, highest temperatures (50/60°C, 60/70°C, 70/80°C and 80/95°C).

It is observed that a larger contraction takes place after an initially smaller thermal expansion. The expansion corresponds to the thermal expansion of the solid and water phases, which is lasting approximately 2.2 hours, due to the rate of heating adopted. In the contraction stage, the shapes of the curves are similar to that of standard consolidation curves, and show that the volume decrease is related to excess pore pressure dissipation. Observation of the curves of the tests carried out at 50 - 60°C and 80 - 95°C, which have been longer (55 and 40 hours respectively) show that the secondary consolidation can reasonably be neglected, even at higher temperature. This is related to the low porosity of the clay.

The thermal consolidation tests presented in Figure 2 are analysed by considering the two relevant equations :

- Fourier's equation of heat transfers : $D_T \nabla^2 T = \frac{\partial T}{\partial t}$ (1)

- Terzaghi's consolidation equation of pore pressure dissipation : $\frac{\partial U(z,t)}{\partial t} = c_v \frac{\partial^2 U(z,t)}{\partial z^2}$ (2)

where c_v is the coefficient of consolidation, and D_T the thermal diffusivity (equal to the ratio K/C , K and C being respectively the thermal conductivity and the volumetric heat capacity). The standard triaxial samples (radius $r = 19$ mm and height $h = 76$ mm) tests were drained by the bottom only (length of drainage 76 mm) and heated by the cell water all around, and by the top and bottom bases. A conservative assumption of radial heating (characteristic length equal to the radius 19 mm) was made. Calculations (see Delage et al. 2000) based on the values of D_T and c_v (taken from Picard 1993 : $c_v = 7.5$ m²/s, $K = 1.7$ W/K/m and $C = 2.85 \cdot 10^3$ J/K/m³, giving $D_T = 5.96 \cdot 10^{-7}$ m²/s) and on the characteristic lengths of heat transfer and pore water dissipation, showed that heat equilibrium was reached much faster (about 10 minutes) than pore pressure dissipation (about 21.5 hours). It confirms that the two phenomena can reasonably be uncoupled. In other words, there is a negligible amount of water drained during the heating phase, which lasts for 1.5 hours. In this phase, the volume increase is due to the thermal undrained expansion of water and minerals. Afterwards, the temperature of the sample is uniform, and the test is similar to a consolidation test at a constant temperature.

Changes in the consolidation coefficient c_v with temperature were deduced from curves of Figure 2, considering the points at t_{50} . Results are reported in Figure 3. The curves show no significant change in the value of c_v with temperature, with an increase from $3.43 \cdot 10^{-8}$ m²/s up to $4.32 \cdot 10^{-8}$ m²/s when temperature is increased from 60 to 70°C, followed by a plateau between 70 and 95°C. This variation is smaller than one order of magnitude, as observed by Habibagahi (1977) on a low plasticity clay ($I_p = 25$, at $T = 25$ and 50°C) and Towhata et al. (1993) on two clays ($I_p = 27$ and 42, at T ranging from 25 to 200°C). The slight changes of c_v observed in Figure 3 is related to two opposite simultaneous effects : the increased temperature increases the permeability of the sample, but this effect is compensated by the decrease of the void ratio.

From a practical point of view, further understanding in the c_v variations and the small changes observed here allow a significantly simpler prediction of the dissipation of the thermal excess pore pressures that occur when the clay is heated in the near field close to a waste isolation gallery.

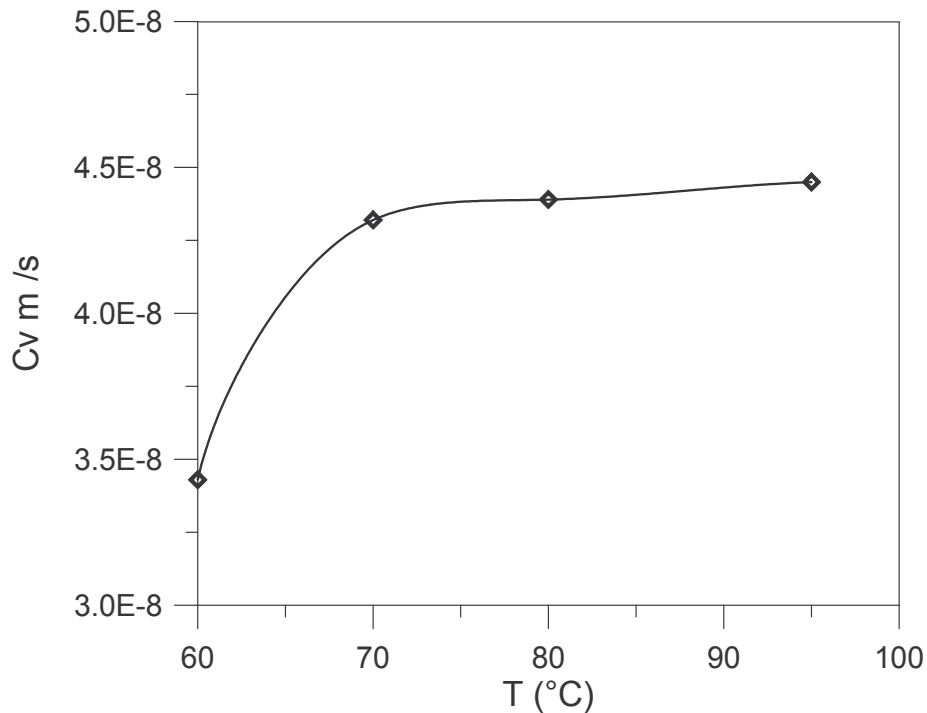


Figure 3 : Variation of the coefficient of consolidation c_v with temperature.

4. EFFECT OF OCR ON THE VOLUME CHANGES

Previous published data have shown that the overconsolidation ratio OCR affects the contracting/expanding nature of the volume change of a clay sample heated under a constant load. On a low plasticity soil ($I_p = 8$) heated from 10 up to 60°C, Paaswell (1967) mainly observed a volume decrease, whereas Plum and Esrig (1969) observed on two clays of different plasticity indexes ($I_p = 11$ and 84) i) a contraction in a normal consolidated state (OCR=1), and ii) no volume change at OCR = 1.7. Similar results were obtained by Baldi et al. (1988), showing that the temperature at which the transition from expansion to contraction occurred was increasing with OCR values. This trend was later confirmed by Towhata et al. (1993) on a remolded MC kaolinite (PI = 29).

In this work, the thermal volume change behavior of Boom clay was examined by submitting samples at various OCRs (OCR = 1, 2, and 12) to temperature increases (22-100°C), or temperature cycles (22-100-22°C). The results obtained are shown in Figure 4. It is observed that the OCR = 1 condition was achieved under confining stresses σ'_c of 1.2 and 3.85 MPa, the OCR = 2 condition was achieved under $\sigma'_c = 4$ MPa and the OCR = 12 condition was achieved under $\sigma'_c = 4.2$ and 6 MPa.

Observation of the results of Figure 4 confirms four major trends of the thermal volume change behavior of Boom clay :

- 1. the plastic contraction of a normally consolidated samples is independent of the mean effective stress applied (see tests at OCR = 1 under 1.2 and 3.85 MPa, and OCR = 12 under 4.2 and 6 MPa). This is in agreement with the observations of Demars and Charles (1982)
- 2. thermal contraction increases with decreasing OCR, leading to contraction only at OCR = 1. This is in accordance with the results of Plum and Esrig (1969), Demars and Charles (1982) and Baldi et al. (1988)

- 3. the slope of the volumetric strain curve in the cooling stage is independent of the applied mean effective stress. The cooling slope is parallel to the slope of the expansion heating phase.
- 4. the temperature at which the transition from thermal expansion to contraction occurs increases when OCR is increased ($T = 50^{\circ}\text{C}$ at $\text{OCR} = 2$, $T = 80^{\circ}\text{C}$ at $\text{OCR} = 12$), in accordance with Baldi et al. (1988) and Towhata et al. (1993).

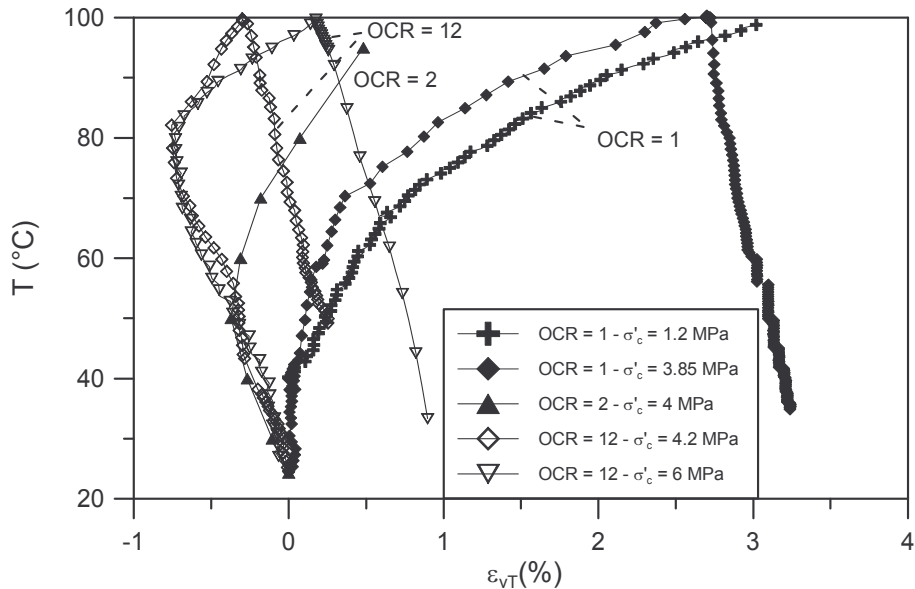


Figure 4 : Volume changes under heating and cooling at different OCR values

These observations confirm that the thermal behaviour of Boom clay is elasto-plastic. In the case of high OCR ($\text{OCR} = 12$ for instance), heating first produces elastic strain that corresponds to the thermal expansion of the soil particles, as demonstrated by the parallelism observed between the cooling slope and the expansion slope. Plastic contraction intervenes afterwards when temperature reaches a certain value. According to standard soil elastoplastic behaviour, an irrecoverable volumetric strain commonly induces a hardening phenomenon that is characterised by an increase of the yield stress. This should also be observed with thermal induced plastic strains. In order to check this point, another set of tests was performed with 4 samples which were :

- 1) isotropically loaded under 4 MPa
- 2) heated at 100°C
- 3) submitted to temperatures equal to 23, 40, 70 and 100°C respectively
- 4) isothermally loaded.

It was expected that the first loading would allow the samples to reach a normally consolidated state ($\text{OCR} = 1$). Heating up to 100°C would induce some hardening of the sample that would be evidenced by subsequent loading at various lower temperatures.

The results obtained (Figure 5) show that the preconsolidation pressures (corresponding to the yield pressure) at various temperatures are all higher than 4 MPa, showing a thermal hardening which is more significant at low temperatures. Since in a $p_{cT} - T$ plane (see Figure 5b) the yield points are aligned, one can conclude that that an exponential expression of the yield pressure as a function of temperature is appropriate.

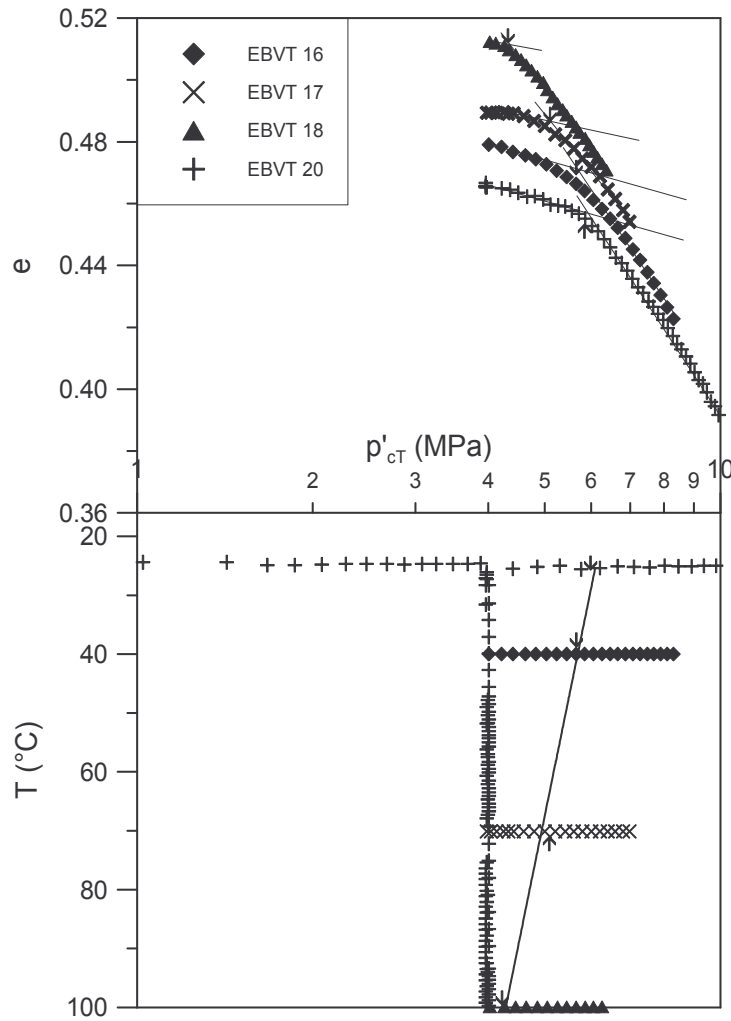


Figure 5 : Isotropic compression tests at different temperatures

5 CONSTITUTIVE MODELLING

Cui et al. (2000) elaborated a multi-mechanism elasto-plastic model which permits to satisfactory describe the thermal elastic plastic behaviour previously observed. The model considers three mechanisms :

- 1. LY mechanism (for Loading Yield) that describes the decrease of the preconsolidation pressure p'_{cT} with increasing temperature, following Eq. 1 :

$$p'_{cT} = p'_{c0} \exp(-\alpha_0 \Delta T) \quad (3)$$

where the initial preconsolidation pressure p'_{c0} , defined by the intersection of LY with the p' axis is a hardening parameter, α_0 is a parameter which governs the curvature of LY.

- 2. TY mechanism (for Thermal Yielding) that describes the thermal plasticity depending on the OCR values, following Eq. 2:

$$T_{CT} = (T_c - T_0) \exp(-\beta p') + T_0 \quad (4)$$

This expression defines a set of exponential curves which cross the temperature axis at a point corresponding to a reference temperature T_c . The parameter β is another hardening parameter that defines the curvature of the curves.

- 3. HC mechanism (for Heating Collapse) that allows the modelling of the transition from expansion to contraction when heating :

$$p' = c_1 p'_{c0} \exp(c_2 \Delta T) \quad (5)$$

where c_1 is the intersection of the HC line with the p' axis, and c_2 is a shape parameter. The asymptote of this curve is the T axis. By definition, the following condition is automatically verified on HC curve:

$$d\varepsilon_{vT} = d\varepsilon_{vT}^e + d\varepsilon_{vT}^p = 0 \quad (6)$$

Eq. 6 means that, on the HC curve, the increment of elastic volumetric strain $d\varepsilon_{vT}^e$ (expansion) is balanced by the increment of plastic volumetric strain $d\varepsilon_{vT}^p$, in such a way that the total variation of volumetric strain $d\varepsilon_{vT}$ is equal to zero. The main advantage of the HC curve is the possibility to consider the production of plastic volumetric strain before the thermal dilation-contraction transition.

Only curves TY and LY are yield curves with specific associated plastic strains. The three curves are presented in Figure 6.

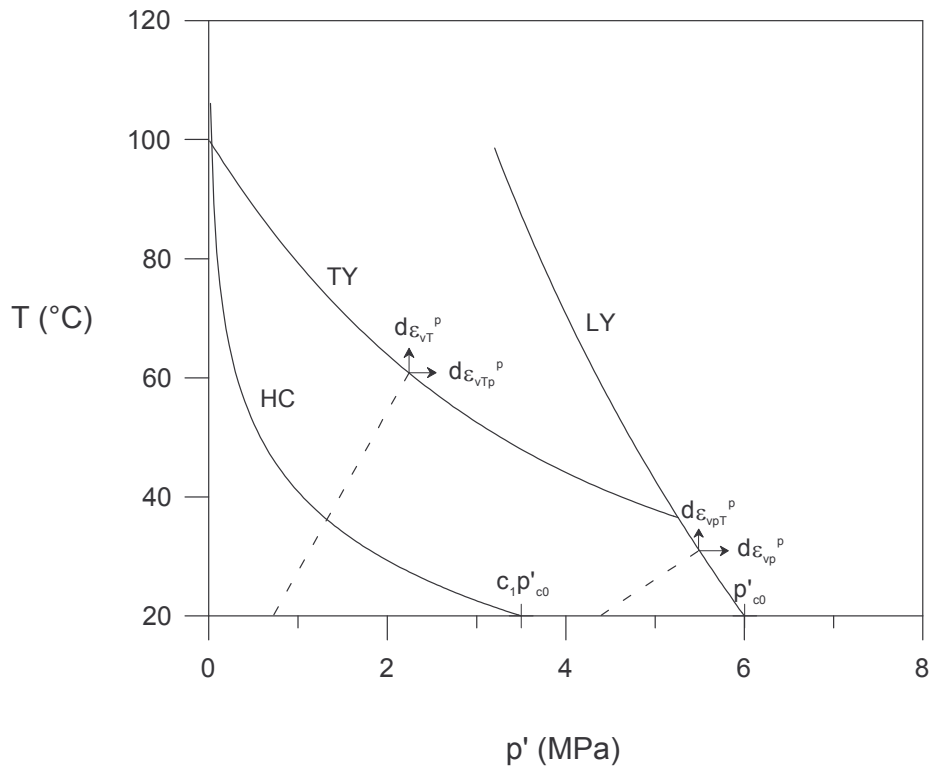


Figure 6 : Yield curves TY and TY, together with heating collapse curve HC (Cui et al. 2000)

In the initial configuration of a soil submitted to the maximum temperature ever supported during its life, TY curve is located below HC curve. For heating tests located on the left side of the intersection between HC and the p' axis, i.e. for $OCR > 1/c_1$, the expanding-contracting behaviour is observed. In other words, the plastic contraction initiated when crossing TY is progressively compensating the elastic expansion, reaching a zero total volume increment in the HC curve. For low OCR values included between $1/c_1$ and 1, the behaviour under heating is only contracting.

In order to model thermal hardening, a coupling rule was defined between TY and LY : any movement of TY due to plastic volumetric strain production ($d\varepsilon_{vT}^p$ or $d\varepsilon_{vTp}^p$) moves LY curve

towards right. It was assumed that the movement of LY had no effect on the TY curve. The performance of the model can be examined by considering the tests carried out by Baldi et al. (1991), in which a Boom clay sample was loaded up to 6 MPa, submitted to a 20-95-20°C temperature cycle, unloaded to 3 MPa (OCR = 2), submitted to a same temperature cycle, unloaded again to 1 MPa (OCR = 6) and also submitted to the same temperature cycle.

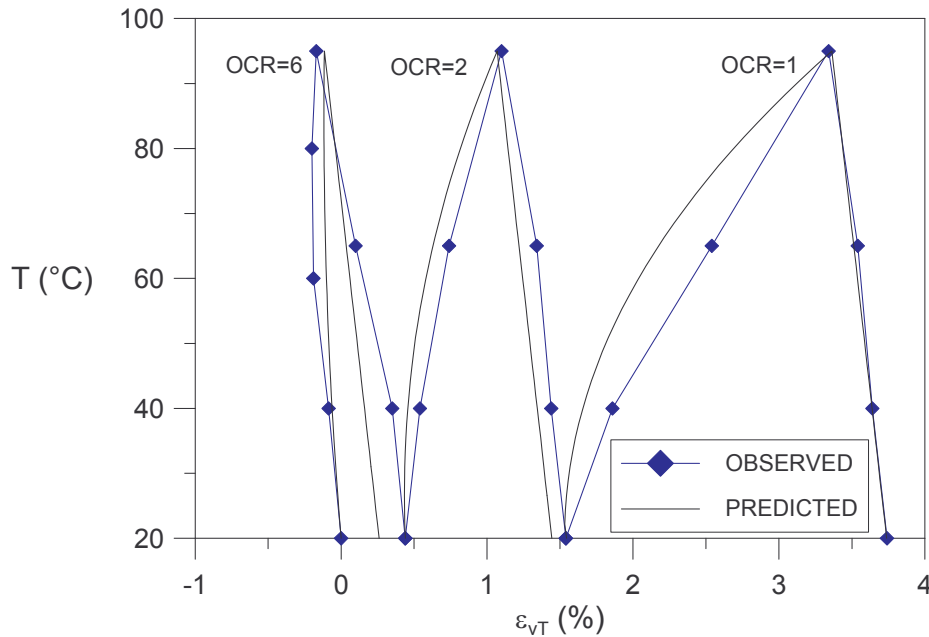


Figure 7 : Simulation of the result of Baldi et al. on Boom clay (1991)

The parameters of the model can be found in Cui et al. (2000). The response of the model is compared to experimental data in Figure 7 for each of the three cycles in temperature. The model appear to provide a satisfactory response : the thermal contraction is larger at low OCR, and the expanding-contracting phase appearing at OCR = 6 is not apparent when OCR decreases.

6. CONCLUSION

The thermo-mechanical behaviour of a potential saturated host clay from Belgium (Boom clay) was investigated using a high pressure triaxial cell. The study of the thermoconsolidation evidenced the pore pressure build-up due to heating and provided some relevant information on the rate of dissipation of the thermally induced excess pore pressures. The significant effects of the overconsolidation pressure on the nature of the volume changes (expansion-contraction) was also investigated. At low OCRs close to one, only plastic contraction was observed whereas an elastic expansion occurred prior to plastic contraction at higher OCRs. Irrecoverable volumetric strains due to contraction had a hardening effect on the soil. It was observed that the pressure of preconsolidation was increased by a previous heating under low OCR.

The model proposed by Cui et al. (2000) has been found appropriate to describe this features of thermo-mechanical behaviour. It provides a useful tool to better predict the situation and the phenomena that will take place in the near field once radial heating from the radioactive waste canister will start.

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