Thermomechanical properties of deep argillaceous formations

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Abstract

A difficulty in the interpretation of mechanical and thermo-mechanical tests on specimens drawn from large argillaceous formations is the strong inhomogeneity of void ratio, clay minerals and carbonates content.

In this paper a relationship is developed to link strength and the maximum preconsolidation stress to the initial void ratio and carbonate content. Compressibility is also correlated to carbonates.

Thermal strains in drained and undrained conditions for a Spanish, a Belgian and an Italian natural clay are compared. In the elastic state strains are comparable, while in the plastic range thermal strains are highest for the Belgian clay, lower in the Spanish cemented clay and lowest in the Italian clay, very stiff and cemented.

1. Introduction

1.1. Motivation

The purpose of this paper is to identify common properties, as well as specific distinctive features of three deep argillaceous sediments with regard to their response to thermo-mechanical loading, particularly at temperatures significant for high-level waste disposal. The materials considered are: the Belgian Boom clay, the Italian Pasquasia clay and the Spanish SS-1 and IC-1 clays coming from two boreholes drilled in the same formation.

Two of the usual characteristics of argillaceous formations of the size needed for disposal of long-lived radioactive waste are heterogeneity and anisotropy. They both influence the interpretation of laboratory results and modelling. Given the limited number of samples, with respect to the extension of the clay formation, the observed mechanical and physical properties turn out to have a significant scatter. Thus, procedures are developed to relate test results between specimens showing different physical properties. Using these procedures thermal strains are discussed. Both drained and undrained heating test results obtained for the three clays are compared. Observed effects of anisotropy are presented and interpreted in terms of a kinematic hardening thermo-plastic model in a companion paper (Hueckel and Pellegrini, 1996).

The thermo-plasticity model developed earlier (Hueckel and Borsetto, 1990) is employed to deal with thermal strain, water pressure buildup and other thermo-mechanical effects.

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1.2. Description of materials

Boom clay is relatively soft, highly plastic with a water content of about 20%. The clay fraction is 22% smectite, 19% illite and 29% kaolinite. This clay has been tested from two batches of material: from $-223$ m (high plasticity index, 46–50; low friction angle, $\phi' = 16$; high void ratio, 0.75) and from $-240$ m (lower plasticity index, 36; higher friction angle, $\phi' = 22$; lower void ratio, 0.5).

Pasquasia clay is a medium plasticity, cemented, sometimes fissured material. The samples, taken at a depth of about 170 m, contained 10–15% kaolinite, 5% smectite, 15–20% illite, and 20–25% calcite; they were characterised by a water content of 13%, by $\phi' = 21–30$ and by a plasticity index of 27.6.

Specimens of Spanish clays came from different depths in boreholes SS-1 and IC-1. In general they have a variable but significant carbonate content, 2–42% (median 13%), a void ratio in the range 0.4–0.64, and a relatively low friction angle, $\phi' = 25–27$. The clay fraction is about 50%, consisting of smectite (25–100%) and illite (0–75%); the plasticity index varies between 18 and 28.

The testing equipment, which is a triaxial apparatus operating at high temperatures and pressures (HITEP), and the testing technique have been described by Baldi et al. (1991).

1.3. Scope of the tests

The experiments undertaken are focused on the mechanical response of saturated clays to heating. The testing campaign was guided by the critical state plasticity theory (Schofield and Wroth, 1968), and in particular by the temperature dependent model developed for clays (Hueckel and Borsetto, 1990; Hueckel and Baldi, 1990; Hueckel and Pellegrini, 1991). The interpretation of results is performed accepting the validity of Terzaghi’s effective stress principle in thermal conditions (Hueckel, 1992).

Heating and cooling tests were performed at various constant stress states in drained conditions. The stress states were in most cases isotropic; a few tests were performed by keeping constant a nonzero deviatoric stress. Undrained heating tests were performed under constant total stress conditions, both isotropic and nonisotropic.

The analysis of the thermo-mechanical behaviour of deep natural clays, considered as potential host rocks of radioactive waste repositories, is made on the basis of a relatively small number of tests, owing to the limited number of specimens available and to the cost of their extraction. Furthermore, even when the specimens are obtained from a single site, they often come from locations varying tens to hundreds of metres in depth, such as in the cases of Boom and Spanish clays, or from boreholes drilled kilometres apart horizontally. Thus, clay specimens often vary with regard to their mineralogical composition, e.g. the smectitic and illitic fractions and the content of carbonates. A nonnegligible variability of physical properties, such as void ratio, water content, plastic and liquid limits, results. The variability of these parameters, here referred to as “physical parameters” of the clay, justifies the differences in the mechanical properties that may be expressed, for the model selected, by: the size of the yield locus, the elastic and plastic moduli and the critical state parameter. Testing each specimen for these parameters would be impractical and often impossible, mainly because some tests are destructive. However, in order to be able to evaluate the results of the thermal tests, the mechanical parameters of each specimen should be known.

Whenever possible, tests should be designed to provide enough data for evaluating as many mechanical and thermo-mechanical parameters as possible from a single specimen, avoiding the poorly controlled influence of inhomogeneity. The multiple triaxial compression test is an example of such a test. In Fig. 1a and b the results of this test are shown for the Spanish clay SS-1. In this test, axial straining (B–C) of a specimen has been stopped when the peak stress (C) has been reached, thus not allowing the material to soften. The specimen is then unloaded (C–D), the confining stress is increased (E) and axial straining (E–F) is repeated up to a new peak stress (F). Further straining allows for strain softening, until the residual strength is reached (G). The specimen is now brought again to isotropic conditions (J) by axial unloading, the confining pressure is lowered...
(H) and another axial straining path is applied (K–L), until a new residual state is attained (L). In this test the following points can be determined (Fig. 1c): points C and F on the virgin (initial) yield surface, \( f_o \); points G and K on a mobilised yield surface, \( f_1 \), and points G, L on the critical state line CSL. Points G and K should theoretically belong to the same yield surface \( f_1 \) (Fig. 1c). Since this did not happen experimentally, the \( f_1 \) locus has been located halfway.

However, the specimen, once tested to failure conditions, cannot be considered any longer as undisturbed, and used for further testing. On the other hand, the interpretation of temperature induced strain in thermo-mechanical tests requires the prior determination of the initial yield surface. This assessment cannot be performed on the same specimen, and another virgin sample may have significantly different properties. Therefore, it becomes necessary to develop an approach which

![Diagram](image-url)

**Fig. 1.** (a) Results of the multiple triaxial compression test TSS-1: deviatoric stress, \( q \), versus axial strain, \( S_3 \) is confining stress. (b) Results of the multiple triaxial compression test TSS-1: volumetric strain versus axial strain. (c) Results of the multiple triaxial compression test TSS-1: the stress points shown belong to the initial and mobilized yield surfaces.
allows to correlate and predict the behaviour of a specimen on the basis of its few physical characteristics. Such an approach is described in the following paragraphs, with reference to the thermo-plastic extension of the Cam-clay model outlined in the next section. The trends experimentally observed in the tested Spanish clays or commonly known empirical relationships are used to develop the correlation.

2. Outline of thermo-plastic cam-clay model

The underlying theory of thermo-plasticity is briefly presented here to set a framework for the test programme. The main features of the thermo-plasticity model, as proposed by Hueckel and Borsetto (1990) for clays are: reduction of the elastic domain (i.e. of the yield limit) with temperature growth (thermal softening), and its expansion during cooling; development of irreversible strains by heating.

The yield surface is modelled by an ellipse in the \( p', q \) invariants plane following formulation of Roscoe and Burland (1968),

\[
f = \left( \frac{p'}{p'_c/2} - 1 \right)^2 + \left( \frac{q}{M p'_c/2} \right)^2 - 1 = 0
\]  

(1)

In Eq. (1) \( p' \) is the isotropic effective stress, \( q \) is the second invariant of stress deviator, reducing to the principal stress difference in the geotechnical triaxial tests configuration, and \( p'_c \) is the apparent maximum past isotropic stress represented by the \( p' \) axis of the yield ellipse.

The principal thermal effect is the shrinking of the elastic domain during an increase of temperature: this happens without stress change. Temperature dependence of the yield domain is modelled through the dependence of the apparent maximum past isotropic stress \( p'_c \) on temperature:

\[
p'_c = p'_{co} \exp \left\{ \lambda + \kappa \left[ (1 - a_o \Delta T)(1 + e_o) \right] \right\} + 2 \Delta T
\]  

(2)

where \( e^t \) is the irreversible thermo-plastic volumetric strain, \( \kappa \) and \( \lambda \) are the elastic and elasto-plastic logarithmic bulk moduli, \( p'_{co} \) is the initial isothermal value of the maximum past isotropic stress, \( A(\Delta T) \) is a negative valued thermal softening function, constrained by the condition that always \( p'_c > 0 \) during the loading process.

The second effect of temperature, that is ductilisation, is described in this model through the constant \( a_o \) of Eq. (2), where it affects the amount of strain hardening at different temperatures. The description of the thermal softening is made by means of the thermal softening function \( A(\Delta T) \), which is uncoupled from that describing the ductilisation \( (a_o \) effect):

\[
A(\Delta T) = a_1 \Delta T + A_2(\Delta T)^2
\]  

(3)

where \( a_1 \) and \( a_2 \) are material constants.

3. Dependence of clay behaviour on physical parameters and its modelling

The mechanical parameters of the model outlined above should describe different initial conditions at different locations due to the inhomogeneity of the physical conditions occurring in an extended clay formation. In the following, an isotropic idealisation of the actual material behaviour is discussed: the model parameters to be related to the physical properties are then scalars. Such parameters are the isotropic apparent preconsolidation stress, \( p'_{cor} \), characterising the initial position of the yield surface, the reference void ratio at unit load, \( e_i \), the critical state coefficient, \( M \), or the ultimate friction angle \( \phi' = \arcsin \left[ 3M/(6+M) \right] \) at the critical state, as well as the elastic shear modulus \( G \) and the elastic and the elasto-plastic logarithmic bulk moduli \( \kappa \) and \( \lambda \), respectively.

For medium to strongly overconsolidated clays, the peak strength under triaxial conditions and the maximum preconsolidation stress in oedometers are empirically linked to soil specific volume, or void ratio, on one hand, and to the content of carbonates on the other hand (Schofield and Wroth, 1968; Lambe and Whitman, 1969). The dependence of the preconsolidation stress on the void ratio is exponential, as implied by most volumetric hardening theories. The maximum pre-
consolidation stress dependence on carbonates content is also nonlinear, but no consensus exists on the applicable relationship. McKown and Ladd (1982) suggest the existence of an upper threshold value of carbonates content, above which an increase of carbonates apparently does not affect the strength of interparticle cement bridges, but rather results in the filling of the interparticle voids. Leroueil et al. (1979) underline the reversibility of cementation.

A procedure, which links the mechanical parameters of the Cam-clay model to physical properties such as the void ratio and the carbonate content, is proposed below. The procedure rests on two principal hypotheses.

First, it is assumed that the maximum preconsolidation isotropic stress attained during the geological process of compaction and the irreversible part of the change in void ratio, \( e_1 - e_g \), between a hypothetical initial state at unit isotropic stress and the maximum preconsolidation stress state, follow a non-linear relationship, analogous to the classical modified Cam-clay relationship (Fig. 2):

\[
(\tilde{\lambda} - \tilde{\kappa}) \ln \frac{P'_c}{P_o} = e_1 - e_g
\]  

(4)

The parameters \( \tilde{\lambda} \) and \( \tilde{\kappa} \) are variable secant elastoplastic and elastic bulk moduli, which depend on the history of carbonation and void ratio development.

The second hypothesis of the proposed procedure is that the final secant elastoplastic and elastic compliances, \( \tilde{\lambda} \) and \( \tilde{\kappa} \) respectively, as well as the reference void ratio \( e_i \) are functions of the final carbonate content. Thus, if the values of \( P'_c \) and \( e_g \) are known for at least two specimens, the parameters \( \tilde{\lambda} \) and \( \tilde{\kappa} \) and \( e_i \), the void ratio at unit stress, can be determined. Instead of \( e_g \), the in situ total void ratio, \( e_o \) can be used, assuming that the elastic part of the strain in such a process is negligible. Finally it should be realised that the secant moduli \( \tilde{\lambda} \) and \( \tilde{\kappa} \) describing a highly non-linear process are expected to be much higher than \( \lambda \) and \( \kappa \) of the linear relationship between the actual, mechanically induced strain and the current (logarithmic) stress.

The available data for the Spanish clays allow to relate the initial yield surface size to the initial void ratio, identifying the former one by means of the one-dimensional, unconsolidated, unconfined, undrained strength, \( \sigma'_u \). It is proposed to express the modified Cam-clay relationship as a function of the one-dimensional strength instead than of the maximum isotropic pre-stress. The relationship between the uniaxial strength and the maximum past isotropic stress is uniquely defined by Eq. (1).

Fig. 3 represents the one dimensional compressive strength value \( \sigma'_u \) of various specimens of the Spanish clays SS-1 and IC-1 against their initial void ratios. The data are grouped into two ranges, that is high/medium and low carbonate content, \( C \), characterised by average values of 0.22 and 0.05 respectively, expressed as CO\(_2\) content. A linear regression was used to find out the relationship between strength and carbonate content, separately for the two ranges, in the form:

\[
\ln \frac{\sigma'_u}{P'_c} = ae_o + c
\]  

(5)

where \( P'_c \) is a reference isotropic stress.

Substituting in Eq. (5) \( P'_c \) for \( \sigma'_u \) by means of Eq. (1), from Eq. (4) one obtains a relationship between mechanical parameters \( \tilde{\lambda} - \tilde{\kappa} \) and \( e_i \) and the coefficients \( a \) and \( c \) in Eq. (5).

The corresponding numerical values of the meters for the low and the medium/high carbonate content range (Fig. 3) are respectively: \( \tilde{\lambda} - \tilde{\kappa} =\)
0.198 and 0.159, while $e_1 = 1.241$ and 1.224. The plastic compliance, $\lambda - \kappa$, consistently decreases with the increasing carbonate content, as expected. The reference void ratio $e_1$ also decreases with the increasing carbonate content, but for the Spanish clay the decrease is very small.

The variations are proposed to be represented by an exponential function, in a way that negative values of $\lambda - \kappa$ and $e_1$ are excluded. This constraint is also in agreement with the already mentioned argument that the growth of the effect of carbonates is limited, once the carbonate content necessary to bridge between the clay particles has been reached. Accordingly, it is proposed:

$$\lambda - \kappa = A_o e^{-\xi C}$$  \hspace{1cm} (6)

$$e_1 = e_{1o} e^{-\chi C}$$  \hspace{1cm} (7)

where $A_o$, $e_{1o}$ are the values of $\lambda - \kappa$ and $e_1$ at zero carbonate content, whereas and are material constants. Their values have been calculated as:

$A_o = 0.211$, $e_{1o} = 1.246$, $\xi = 1.27$, $\chi = 0.0798$.

The elastic bulk modulus too is considered dependent on carbonate content. For the Spanish clay samples from boreholes SS-1 and IC-1, this dependence is plotted in Fig. 4. The modulus decreases over three times within the range of the carbonate content variation. The correlation is expressed by the exponential function:

$$K = K_o e^{-\zeta C}$$  \hspace{1cm} (8)

and the values of the coefficients were found as $K_o = 0.0245$ and $\zeta = 6.621$.

The data on Spanish clays do not indicate any consistent correlation between the residual friction angle (or the critical state parameter) and the plasticity limit, plasticity index or clay fraction content.

To verify the effectiveness of the proposed relationships, the comparison between the experimentally obtained peak strengths for different specimens and the predictions of their behaviour following the above developed formulas has been made: the results are shown in Fig. 5. The prediction of the initial yield surface position for
Fig. 4. Elastic bulk logarithmic modulus versus carbonate content for a deep Spanish clay.

specimens SS-1, SS-6 and SS-16, for which peak strength values are available, were performed using Eqs. (1, 4, 5) rewritten in the form

$$p'_{co} = p'_o \exp \frac{-[e_o - e_{1d} \exp (-\chi C)]}{\Lambda_o \exp (-\zeta C)}$$

where $p'_o$ was taken as 0.1 MPa. The physical parameters of the specimens and the calculated values of $p'_{co}$ and $\sigma'_1$ are given below, taking $M=1.18$.

Fig. 5 shows that while the strength for specimens SS-1 and SS-16 is fairly well predicted, that for SS-6 (Table 1) is somewhat exaggerated. However, data on the carbonate content of this specimen are uncertain.

As already mentioned, Boom clay has no carbonates. However, physical properties between the

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$e_o$</th>
<th>$C$</th>
<th>$p'_{co}$ (MPa)</th>
<th>$\sigma'_1$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS-1</td>
<td>0.49</td>
<td>0.237</td>
<td>10.13</td>
<td>4.07</td>
</tr>
<tr>
<td>SS-6</td>
<td>0.39</td>
<td>0.079</td>
<td>8.31</td>
<td>3.34</td>
</tr>
<tr>
<td>SS-16</td>
<td>0.57</td>
<td>0.198</td>
<td>5.46</td>
<td>2.19</td>
</tr>
</tbody>
</table>
two levels are visibly different: the initial void ratio is about 0.5 at $-240$ m and 0.75 at $-223$ m; the plasticity limits are 16% and 22–25%, the plasticity indexes 27–35 and 46–50, and the clay content 45% and 61%, respectively. Also, there is a visible inhomogeneity in its mechanical properties (Baldi et al., 1991, vol. 1). In particular, differences are visible in the residual strength parameter $M$, 0.87–1.0 versus 0.6, and thus in the friction angle. The elastic shear modulus has corresponding values of about 100 MPa versus 80 MPa at a confinement representative of the plastic range (5–6 MPa). Differences in elastic and plastic bulk moduli as well as in terms of preconsolidation stress are also quite insignificant. Given the fact that the decrease in the apparent preconsolidation

![Diagram](image_url)

**Fig. 6.** (a) Volumetric strain during drained heating and cooling in drained conditions at constant isotropic stress of 1.0 and 7.0 MPa in the test SS-4 on a Spanish clay. The strain is calculated from the volume of water expelled from the specimen during heating.
4. Thermo-mechanical properties

Thermo-mechanical testing was performed in drained or undrained conditions to simulate two extreme scenarios of slow or relatively fast thermal or mechanical loading.

The test-programmes were guided by the thermo-plasticity theory for clays outlined in Section 2. Series of drained heating tests at different constant effective isotropic stress values were performed to quantify thermal strain. Heat was applied very slowly, under computer controlled zero pore pressure regime. The results of such tests for the three deep clays are shown in Fig. 6a, b and c. The thermal volumetric strain was calculated using the relationship between the volume of water expelled from the specimen during heating and the volume increase due to the nonlinear thermal expansion of pore water and of the solid skeleton, as originally proposed by Campanella and Mitchell (1968). However, the assumption that clay water expands as bulk water has been found inconsistent with the experimental results in dense clays and leading to an underestimation of the thermal strain of the clay skeleton (Baldi et al., 1988). Dehydration of adsorbed water caused by heating, in addition to a presumably smaller thermal expansion, makes the determination of volumetric strain hypothesis-dependent. To avoid such inconvenience, the directly measured axial strain should be used. In clays with a significant degree of anisotropy the same measurement should be carried out for the lateral strain. The measure of lateral strain can be obtained indirectly by reading the axial strain in a horizontally trimmed specimen.

The results obtained for the three clays show a consistent pattern of strong effective stress dependence. Also common to the three materials is the occurrence of an expansive volumetric thermal strain at low confining stress values, and of contractive strain at high confining stress values. In terms of thermo-plasticity theory (Hueckel and Borsetto, 1990), this difference is due to the different position of the effective stress point with respect to that of the yield surface at the onset of heating, that is to a different initial overconsolida-
Consider for instance the thermal strains of the Spanish clay depicted in Fig. 6a. The specimen heated in test TSS-4 was rather weak, with a relatively high void ratio (0.561) and a low carbonate content (CO₂=0.057). For these values, \( p'_{co} \), predicted according to Eq. (9), was 3.19 MPa. During heating, thermal softening occurs, that is the yield surface shrinks with temperature, as described by Eqs. (2, 3).

It appears from the results of heating at 1 MPa that the thermal softening at 100°C was still insufficient for the material to undergo irreversible deformation, as observed after cooling back the specimen to room temperature. In fact cooling is assumed to produce a return of the yield surface to its original position, if no plasticity is involved in the heating process. After cooling at 1 MPa, an isotropic stress of 7 MPa was applied, and then the heating-cooling cycle was repeated at this higher confining stress. The loading process from 3.19 MPa to 7 MPa should be theoretically a plastic one, and thus the heating should entirely occur in the plastic range. All the additional strains measured during heating are thus considered thermo-plastic. The yield surface does not change during heating in a plastic state if the stress is kept constant. Otherwise, according to the theory of plasticity, an inadmissible situation would occur: the current stress point would be left outside the current yield locus undergoing thermal softening. Thus, compressive plastic strains inducing strain hardening are generated to compensate for thermal softening. Indeed, in the experiment the heating strains at 7 MPa are compressive and irreversible. In fact, during cooling, the volumetric strain was again compressive and had a similar shape to that observed during “elastic” heating at 1 MPa.

Comparing the three materials Spanish, Boom and Pasquasia clays, it may be concluded that their thermal strains are similar. The differences of elastic thermal expansion at 1 MPa are not substantial. The irreversible contractive thermal strain is almost two times smaller in SS-1 clay at 7 MPa than in Boom clay at 6 MPa. Pasquasia clay produced even less irreversible contraction than the SS-1 specimen. The situations of the tests on SS-1 and Boom clays were not directly comparable, because the Boom clay specimen was subjected to cooling at 3 MPa, which should have brought the yield surface well beyond 6 MPa, so that heating at 6 MPa started in a fully thermo-elastic mode. It may be hypothesised that in Boom clay the thermal strain at 6 MPa was elastic (or expansive) up to 35–40°C. This consideration emphasises
the importance, and also the difficulty, of an accurate estimate of the initial position of the yield surface, which is analogous to the evaluation of the apparent preconsolidation stress and OCR in other soil mechanics problems.

The undrained heating tests were undertaken to learn about pore water pressure development during heating. In particular, the possibility of thermal failure was investigated, as discussed in earlier papers by Hueckel and Pellegrini (1991), Hueckel and Pellegrini (1992). Thermal expansion of clay, even at very low confining...
effective stress is much lower than that of pore (bulk) water. This difference results in a significant water pressure buildup during heating. The resulting drop of effective stress, at nonzero stress deviator, may lead to specimen failure, if the increase of isotropic effective/deviator stress ratio, reaches the critical state value, \( \eta = M \). Fig. 7a and b presents for the case of the Spanish clay (sample TSS-3) the axial strain and water pressure changes versus temperature, while Fig. 7c shows the development of water pressure against axial strain, in a heating test carried out at a constant total stress of \( q = 2 \) MPa and \( p = 3 \) MPa in undrained conditions.

The portion 1-2 of the strain history is a device effect due to the friction between the loading rod and its bearing. At 52°C, a significant compressive strain rate developed and pore water pressure dropped. The first portion of this drop (3-4) occurred without strain: it can be interpreted as a result of internal pressure redistribution inside the specimen. The portion (4-5) is interpreted as a dissipation of the excess water pressure, which cannot be maintained beyond the peak failure locus bounding the "dry" side of the yield domain (\( p' \leq p'_{co}/2 \)).

Using Eq. (9) with a void ratio of 0.447 and a low carbonate content (\( \text{CO}_2 = 0.057 \)) the value of the estimated initial precompression stress is \( p'_{co} = 5.86 \) MPa. As temperature increases, the yield surface shrinks due to thermal softening while the isotropic effective stress migrates at constant \( q \) toward the critical state line (\( \eta = M \)).

The effective stress determined by the pore water pressure excess at constant total stress (Fig. 8) indicates that, for an elastic limit drawn through point 3, corresponding to the maximum pore water pressure reading (1.9 MPa), the apparent isotropic precompression stress \( p'_e \) would be about 3.71 MPa. At 52°C, the actual elastic domain sketched in Fig. 8 may be even smaller leaving the effective stress out of the domain. As previously stated, this is inadmissible in terms of plasticity, while, actually, it may be explained as a viscoplastic strain softening occurring until the stress excess is dissipated (point 5 in Fig. 8).

Upon cooling to about the initial temperature, a net pore water pressure deficit of 0.7 MPa is observed respect to the start of the test. It can be explained by the formation of a larger pore space caused by heating respect to the initial conditions, that is by a dilatancy of the clay skeleton. The vertical net irreversible strain being compactive, the only explanation for dilatancy can come from lateral expansion, which is in agreement with the applied theory. It can be concluded that thermal failure occurred at point 5, that is at the intersection of the effective stress path with the critical state line.

It should be noted that the axial strain, during the heating portion of the test (1-4), is dilative all the time. Thus, as seen in the representation given in Fig. 9a, in such process the response is elastic. During strain softening (2-3), both the axial components of the elastic and the plastic strain rate are contractive (Fig. 9a), while the lateral dilation is plastic.

Thermal failure in Boom clay and in Pasquasia clay occurred according to an alternative scenario, still theoretically consistent (Fig. 9b, Hueckel and Pellegrini, 1991). A substantial compressive plastic strain developed throughout an extensive range of temperatures (Fig. 10).

Comparing the three clays, it may be concluded that the thermo-elastic strains in drained tests at 1 MPa are very similar in all three materials (Fig. 6a, b and c). It appears that the rate of
Fig. 9. (a) Thermo-plastic strain softening during undrained constant nonisotropic stress heating according to the thermo-elasto-plastic model by Hueckel and Borsetto, 1990. (b) Thermo-plastic strain hardening during undrained constant nonisotropic stress heating according to the thermo-elasto-plastic model by Hueckel and Borsetto, 1990.
Fig. 10. Undrained heating tests on Boom clay at $q = 1$ MPa and $p = 1.98$ MPa (after Hueckel and Pellegrini, 1992): pore water pressure change with axial strain.
Fig. 11. Undrained heating tests on Pasquasia clay at $q = 2$ MPa and $p = 3$ MPa: pore water pressure change with temperature.

thermal softening, that is the rate of change of $p'_e$ with temperature, must be lower in the Spanish clay than in Boom clay. This is confirmed by the fact that the Spanish clay produced much smaller plastic strain at comparable effective stresses. As far as temperature to failure is concerned, it has been much lower for the Spanish clays than for Boom and Pasquasia clays. However, it should be reminded that the temperature to failure is not a material parameter and it depends strongly on the overconsolidation ratio and on the stress deviator value applied to the specimen in the test. The net final pore pressure differences at failure respect to the estimated in situ effective stress were: 1 MPa/52°C in Spanish clay, 2 MPa/90°C in Boom clay, and 1 MPa/65°C in Pasquasia clay.

The final drop of pore water pressure, remarkable in the stiffer clays (ref. points 4-5 in test TSS-3, Fig. 7 and K-N in Pasquasia clay, Fig. 11), requires further examination: it may be linked to a thermally enhanced dilatancy or to an excessive heating rate. A microstructural study is also recommended to verify whether there is any relation to possible microfracturing and dehydration.

5. Conclusions

Mechanical and thermo-mechanical properties of three deep clays are discussed. The clays are quite different mineralogically, with high to low plasticity index, high to negligible carbonate content and a variability in organic matter as well. A procedure proposed to correlate mechanical and thermo-mechanical properties, described by a thermo-plastic version of the Cam-clay model for specimens of the same material having different physical properties, has given promising results.

Thermo-mechanical drained and undrained test results were compared for the three clays. Thermal strains show a similar pattern of expansion in all three materials; in the elastic range they are expansive at low confining stresses and contractive at high confining stresses. Spanish clays develop lower plastic strain during heating.

In some Spanish clay specimens, undrained tests have shown samples failure at relatively low temperature.

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References


