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# Modelling the Response of Clay at Elevated Temperature

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**Summary:** A program of tests has been conducted to explore the behaviour of an illitic clay at temperatures varying from 22°C to 100°C. This paper presents some of the key experimental findings from this study and discusses the capability of existing constitutive models to reproduce this behaviour. For the purposes of comparison, a constitutive model proposed by Cui et al (2000) that can describe the thermo-mechanical behaviour is used. This is the most recent of a family of Modified Cam Clay type models that have been developed to describe the effects of changing temperature. The model is used to predict the behaviour of drained and undrained heating and the subsequent isothermal shear response. It is shown that the model can make reasonable predictions of the behaviour, but the selection of parameters, in particular controlling thermal yield, is not straightforward. Some comments on the limitations of existing models are made.

## INTRODUCTION

Geotechnical researchers have become increasingly interested in the engineering properties of soils at elevated temperature. One of the main reasons has been the interest in the disposal of hot radioactive wastes. The safe disposal of the wastes from nuclear facilities has presented novel challenges to Geotechnical Engineers and has led to the development of several experimental disposal facilities. There are many other applications that require an understanding of the effects of elevated temperature on soil behaviour, such as the burial of high voltage cables; heat storage; extraction of geothermal energy; and foundations subjected to temperature fluctuations. Several numerical and constitutive models have been developed to simulate the thermo-mechanical behaviour of soil, but their acceptability remains to be verified by further and more accurate experimental studies. In this paper, the applicability of one of the most recent of these soil models, the thermo elasto-plastic model of Cui et al (2000), is investigated by comparing its predictions with the experimental results from triaxial tests of an illitic clay, M44. Some of the shortcomings of the models are discussed.

Mathematical and constitutive models have been developed by many researchers to describe the thermo-mechanical behaviour of soils. These models are mainly extensions of the Modified Cam-Clay model proposed by Roscoe and Burland (1968). Hueckel and Borsetto (1990) were among the first researchers who proposed an extension to elasto-plastic Cam-Clay model using Prager's thermo-plasticity theory. A quantitative validation of this model was made by Hueckel and Baldi (1990). The main extension to Modified Cam-Clay was in allowing the elastic region to shrink with increase in temperature (thermal softening) and to expand during cooling. For soil that was yielding, plastic strain hardening and thermal softening could occur simultaneously. Tanaka et al (1997) explicitly studied the effects of heating on yield loci and confirmed that the elastic domain shrunk during heating and expanded upon cooling. One of the limitations of these models is that they are unable to account for the dependency of volumetric strain on over-consolidation ratio (OCR) as soil temperature is raised. To overcome this limitation, more sophisticated models have been proposed by Graham et al (2001) and Cui et al (2000). As a key assumption of Graham et al's model, an increase in volumetric compressibility with temperature, is not consistent with the experimental data, the model of Cui et al (2000) has been explored further in this paper.

## EXPERIMENTAL PROCEDURE AND RESULTS

A fully automated high (150°C) temperature triaxial apparatus (FHTTA) has been designed and developed in the University of Sydney at the Centre for Geotechnical Research (CGR) by Ghahremannejad (2003). Tests were carried out on cylindrical samples of Kaolin C1C (LL=63, PI=31) and M44 illitic clay (LL=60, PI=25) with a diameter of 50 mm and a height to diameter ratio of approximately 2 to 1. All experiments were carried out using both radial drainage and drainage only from the base. Tests were performed with elevated back pressures of 200 kPa for tests at room temperature and 500 kPa at elevated temperatures. These values were sufficient to ensure saturation and to prevent pore water from boiling. The samples were consolidated, following various thermo-mechanical consolidation paths, before shearing at effective stresses ranging from 100 kPa to 700 kPa and at temperatures between 22°C and 100°C.

The results were generally consistent with a number of other studies that have explored the effects of elevated temperature on soil behaviour (e.g. Campanella and Mitchell, 1968, Towhata et al, 1993, Hueckel and Baldi 1990). They showed that deformation of normally consolidated (NC) samples during drained heating is mainly plastic and not recoverable upon cooling. For NC samples, the thermal compression curve is independent of effective stress. On cooling and re-heating, the deformations are predominantly elastic and appear to simply reflect the expansivity of the soil's solid particles. The compression and swelling response is analogous to the response of soil to increase and decrease of mean effective stress, p'. During undrained heating at constant stress, pore pressures develop because the water expands more than the solid particles. When subjected to undrained thermal cycles, NC and over-consolidated (OC) samples of M44 clay both indicated similar repeatable hysteresis loops in specific volume, v-p' plane, and a relationship between v and temperature, T that was non-linear but reversible and repeatable. This indicates that during undrained heating, the thermal volume changes are primarily a consequence of the thermal expansion of water and clay particles. The isotropic normal consolidation line (INCL) in the v-p' plane can be described by:

$$v = N - \lambda \ln p' \qquad (1)$$

The data show a family of INCL lines all with the same slope, $\lambda$, but with different intercepts, N, at p' = 1 kPa. depending on the temperature. The slope of the unload-reload lines, $\kappa$, has been found to reduce with increase in temperature and effective stress level (during mechanical unloading). The slope of the critical state line (CSL) in the q-p′ plane, M, reduces with temperature, while its trace in the v-p' plane is also a function of temperature. The CSL in the v-p' plane is given by

$$v = \Gamma - \lambda \ln p' \qquad (2)$$

and has the same slope as the INCL, $\lambda$, but its intercept, $\Gamma$ reduces. at higher temperatures. The vertical separation between the INCL and CSL in the v-p' plane, given by N - $\Gamma$, slightly reduces with temperature.

The undrained shear strength of NC and lightly OC samples of M44 clay decreased slightly at elevated temperature and was found to be independent of the thermo-mechanical consolidation path (i.e. the order of heating and stress application). The drained shear strength of NC samples increased with temperature while the ductility reduced. The normalized shear stiffness of NC samples of M44 clay at small strain clearly reduces with increase in temperature, but there are no significant changes with temperature in the stiffness of OC samples (same OCR and $p'_c$). For NC samples the normalized secant modulus at 50% of the shear strength, $G_{50}/p'_c$, decreases with increasing temperature during undrained shearing but remains unchanged for drained shear tests.

## THERMO-ELASTO-PLASTICMODELLING

In this section, the main equations describing the thermo-elasto-plastic model proposed by Cui et al (2000) are presented. The elastic volume strain is given by:

$$d\varepsilon_v^e = \alpha_2 dT + \frac{\kappa}{v}\frac{dp'}{p'} \qquad (3)$$

Parameter $\alpha_2$ is the thermal expansion coefficient of the drained soil and is used for calculation of the elastic thermal strain.

Two yield curves in the T-p' plane are used to describe the plastic strains and these are referred to as the loading yield (LY) and thermal yield (TY). The LY locus is given by:

$$p'_{cT} = p'_{c_0} \, exp(-\alpha_0 \Delta T) \qquad (4)$$

where $p'_{cT}$ is the yield pressure at temperature $T$, $p'_{co}$ is the pre-consolidation pressure at the reference (room) temperature, $T_0$, and is given by the intersection of LY with the p' axis, and $\alpha_0$ defmes the curvature of LY locus. $p'_{co}$ is a hardening parameter. The LY curve defines the reduction in size of the elastic region that occurs on heating. The TY (thermal yield) locus is given by:

$$T_{CT} = (T_C - T_0)\, exp(-\beta p') + T_0 \qquad (5)$$

where $T_C$ is a reference temperature corresponding to the intersection of TY with the T axis, and $\beta$ is a hardening parameter that defines the curvature of the TY yield locus. Any thermo-mechanical path crossing TY will generate thermal plastic strain and reduce the hardening parameter $\beta$ while $T_C$ remains constant. Thermal yield (TY) is activated by heating in the range of higher OCRs. If an OC sample is heated up to a temperature higher than the maximum temperature that has ever been supported by the soil, this will lead to plastic strain. Within the region defined by TY and LY, any changes in temperature or mean effective stress cause only elastic strains. When the loading path crosses the LY curve, the plastic volumetric strain due to mechanical loading, $d\varepsilon^P_{vm}$, can be evaluated using the following equation:

$$d\varepsilon_{vm}^{p} = \frac{\lambda - \kappa}{v}\frac{dp'_{C_0}}{p'_{C_0}} \tag{6}$$

If mechanical loading at constant temperature approaches the TY yield curve, the mechanical plastic strain can be calculated from the following expression:

$$d\varepsilon_{vTm}^{p} = \alpha_1 \frac{dp'}{P} \tag{7}$$

where $\alpha_1$ is a parameter to describe the thermal over consolidation effects observed by Towhata et al *(1993)* and Sultan *(1997)* when a NC sample is mechanically consolidated after thermal consolidation. To determine the plastic volume strain due to change of temperature, Cui et al (2000) proposed the following empirical equation:

$$d\varepsilon_{vT}^{p} = \alpha_p [exp(\alpha_p \Delta T) - a] dT \tag{8}$$

where $\alpha_p$ and "a" are parameters related to the slope and the shape of the thermal plastic strain curve respectively. The experimental data for M44 clay and other studies (e.g. Demars and Charles *1982)* show that the parameters are constant for normally consolidated soil and independent from the applied stress. To enable $a$,, to be determined at higher OCRs, Cui et al *(2000)* made use of the easily observed transition between expansive and contractive volume strains that can be described by a locus in T - p' space. This is called the HC locus and is defined by the following equation:

$$p' = C_1 p'_{C_0} exp(C_2 \Delta T) \tag{9}$$

where $C_1$ is the intersection of the HC curve with the p' axis and $C_2$ is a shape parameter. For OCRs greater than $1/C_1$, the expansion-contraction behaviour is expected. For OCRs between *1* and $1/C_1$. the sample only contracts upon heating.

The hardening rule is governed by two hardening parameters, β and $p'_{Co}$. The movements of TY and LY yield curves are defined through the following hardening laws:

$$d\beta = \frac{-exp(\beta p')}{p'(T_c - T_0)\alpha_p [exp(\alpha_p \Delta T) - a]} d\varepsilon_{vT}^{p} - \frac{\beta}{\alpha_1} d\varepsilon_{vTm}^{p} \tag{10}$$

$$\frac{dp'_{Co}}{p'_{Co}} = \frac{\alpha_0}{\alpha_p [exp(\alpha_p \Delta T) - a]} d\varepsilon_{vmT}^{p} + \frac{v}{\lambda - \kappa} d\varepsilon_{vm}^{p} \tag{11}$$

The coupling of the two mechanisms leads to:

$$\frac{dp'_{Co}}{p'_{Co}} = \frac{\alpha_0}{\alpha_p [exp(\alpha_p \Delta T) - a]} d\varepsilon_{vmT}^{p} + \frac{v}{\lambda - \kappa}(d\varepsilon_{vm}^{p} + d\varepsilon_{vTm}^{p}) +$$

$$+ \{\frac{\alpha_0}{\alpha_p [exp(\alpha_p \Delta T) - a]} + k_1 [\frac{v}{\lambda - \kappa}]\} d\varepsilon_{vT}^{p} \tag{12}$$

To fully describe the soil behaviour, another plastic mechanism describing the deviatoric soil response is required, and this is provided here by the Modified Cam-Clay model (Roscoe and Burland, *1968).* The yield locus in the q-p' plane is an ellipse and is defined as:

$$f = q^2 - M^2 [p'(p'_{c_0} - p')] = 0 \tag{13}$$

where $p'_{c0}$ is the stress controlling the size of yield locus. The assumption of normality leads to the plastic potential being given by the same relationship. In other words, the plastic strain tensor is in the direction normal to the yield locus, and the associated flow rule is defined as:

$$\frac{d\varepsilon_{v}^{p}}{d\varepsilon_{s}^{p}} = \frac{M^2(2p' - p'_{c_0})}{2q} \tag{14}$$

where $d\varepsilon^{p}_{s}$ is the increment of plastic shear strain. Triaxial shearing tests were carried out only under isothermal conditions, and the elastic and plastic volumetric strains during deviatoric loading are simply given by equations *3* and *7* respectively. The elastic and plastic shear strains can be determined from the following expressions:

$$d\varepsilon_{s}^{e} = \frac{dq}{3G} \tag{15}$$

$$d\varepsilon_{s}^{p} = \frac{(\lambda - \kappa)}{vp'(M^2 + \eta^2)}[2\eta dp' + \frac{4\eta^2}{(M^2 - \eta^2)} dq] \tag{16}$$

where $\eta = q/p'$ is the stress ratio.

## PARAMETERS

The following parameters have been determined from the experimental data to model the thermo-mechanical behaviour of M44 clay: $\alpha_S = 0.35\text{x}10^{-4}\ ^\circ\text{C}^{-1}$, $\alpha_0 = 3.99\text{x}10^{-3}\ ^\circ\text{C}^{-1}$, $\alpha_1 = 0$, $\alpha_2 = -1.82\text{x}10^{-5}\ ^\circ\text{C}^{-1}$. $T_C = 522^\circ\text{C}$(Test14) and 142°C(Test17), $C_1 = 0.4$, and $C_2 = -1.47\text{x}10^{-2}\ ^\circ\text{C}^{-1}$. $a = 1.00578$. The parameters describing the deviatoric response are given in Tables 1 and 2. Table 1 gives values, AN, $\Delta\Gamma$ indicating the shifts in the INCL and CSL lines and the vertical separation between them with temperature. The average shifts are 0.017 and 0.012 for every 25°C temperature increment and the vertical separation, N-$\Gamma$. varies with temperature and is not in general equal to $(\lambda\text{-}\kappa)\ln 2$. as assumed in the Modified Cam-Clay model. To simplify the modelling, it has been assumed that the separation of the INCL and CSL lines is independent of temperature as also assumed in other studies (e.g. Seneviratne et al, 1993, Graham et al, 2001). This has been achieved by adjusting $\Gamma$ and $\kappa$ to the (starred) values in Table 2, so that (N-T) and (h-K) ln2 are always equal to the average value of 0.0958. In the model, $\kappa$ is considered temperature independent, whereas the experimental data and other studies (Campanella and Mitchell, 1968 and Despax, 1976) show slight reductions in $\kappa$ with temperature.

Table 1. Shifts and vertical separations of INCL and CSL with temperature

| Temperature °C | $\Delta$N | $\Delta\Gamma$ | Temperature °C | N-$\Gamma$ | $(\lambda-\kappa)$ln2 |
|---|---|---|---|---|---|
| 22 | - | - | 22 | 0.1053 | 0.0908 |
| 22-50 | 0.0163 | 0.0072 | 50 | 0.0962 | 0.0921 |
| 50-75 | 0.0201 | 0.0169 | 75 | 0.093 | 0.0933 |
| 75-100 | 0.0146 | 0.0103 | 100 | 0.0887 | 0.0946 |
| Average | 0.017 | 0.012 | Average | 0.0958 | 0.0927 |

Table 2. Observed and assumed (starred) model parameters

| Temperature °C | N | N | $\Gamma$ | $\Gamma^*$ | $\lambda$ | $\kappa$ | $\kappa$ | M | $\mu$ |
|---|---|---|---|---|---|---|---|---|---|
| 22 | 2.8417 | 2.8417 | 2.7364 | 2.7459 | 0.164 | 0.033 | 0.026 | 0.9 | 0.25 |
| 50 | 2.8254 | 2.8247 | 2.7292 | 2.7289 | 0.164 | 0.031 | 0.026 | 0.87 | 0.25 |
| 75 | 2.8053 | 2.8077 | 2.7123 | 2.7119 | 0.164 | 0.029 | 0.026 | 0.85 | 0.25 |
| 100 | 2.7907 | 2.7907 | 2.7020 | 2.6949 | 0.164 | 0.028 | 0.026 | 0.83 | 0.25 |

## ISOTROPIC THERMO-MECHANICAL CONSOLIDATION

In order to investigate the validity of Cui et al's model regarding the thermo-mechanical volumetric strains of M44 clay, experimental results from two tests, (tests 14 and 17), are considered here. Figure 1a shows the thermo-mechanical path and variations of yield loci with thermo-mechanical loading for test 14. For clarity, only the stage with thermal loading is considered. The sample was initially consolidated (mechanically) to p' = 700 kPa and unloaded to p' = 100kPa (OCR = 7). Then it was heated to 100°C under constant mean effective stress (1-2). The initial mechanical loading results in the $LY_0$ locus crossing the p' axis at 700 kPa, and unloading from this point produces elastic mechanical strain. At point 1, the sample has not experienced any temperature elevation so the $TY_0$ curve is very close to the p' axis. From point 1 to 2 (heating from 22°C to 100°C), the consolidation path crosses the $TY_0$ locus, giving rise to plastic compressive thermal strain. The resultant thermal strain (elastic and plastic) is expected to be expansive until the path crosses the $HC_0$ curve at 78°C after which contraction is observed. In consequence the $TY_0$ curve moves to $TY_1$. The plastic strain also

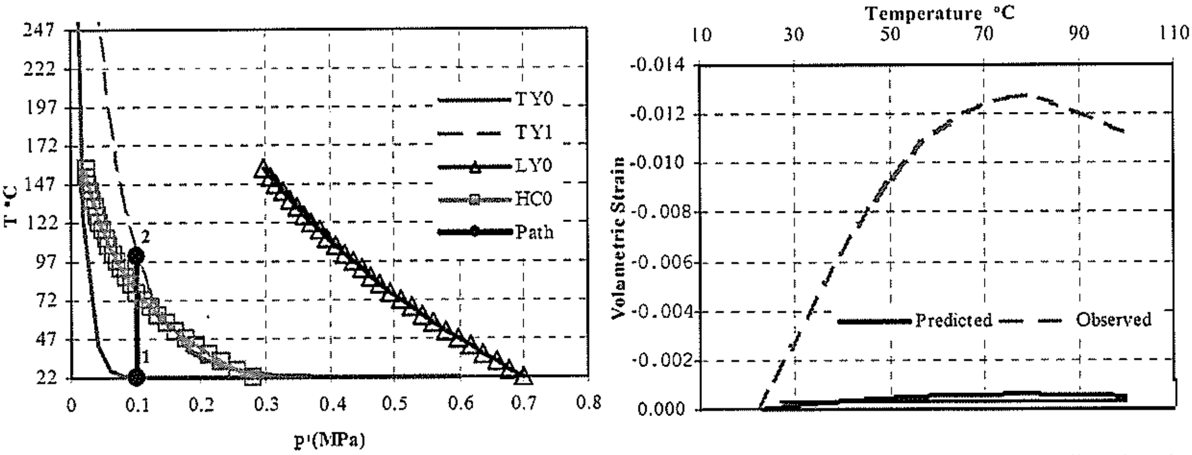

Figure 1. (a) Thermo-mechanical path for Test 14 (OCR = 7), and (b) comparison between predicted and observed volumetric strain for M44 clay

results in an increase in LY but because the strains are small this is not significant. The changes in volumetric strain with temperature are demonstrated in Figure 1b. The model reproduces the observed pattern of expansion then contraction, however, it can be seen that the predicted volumetric strains are much less than the observed values. The model shows maximum expansive volume strains of about 0.1% while the observed values indicate about 1.3%. The discrepancy between the observed and predicted volumetric strain in this case, could arise from shortcomings of the model or incorrect parameter determination. For example, the model assumes that expansive volumetric strains arise only from expansion of solid particles, whereas there could be some additional expansion due either to water absorption at high OCR or to creep, or alternatively the value of $\alpha_2$ that was estimated from the thermal cycle of a normally consolidated sample could be inappropriate at high OCR.

Figure 2a demonstrates the thermo-mechanical path followed during consolidation of test 17 in the T-p' plane. The initial mechanical consolidation to p' = 400 kPa has been omitted for clarity. At point 1, the sample is normally consolidated and the thermal yield locus (TY$_0$), loading yield locus (LY$_0$) and the transition curve (HC$_0$) all are at initial states since no temperature changes have occurred. The sample is heated to 100°C keeping the mean effective stress constant (1-2). During this sequence, the consolidation path crosses both TY$_0$ and LY$_0$ curves at the start of heating and induces thermal plastic contraction, which in turn moves all three loci to HC$_1$, LY$_1$ and TY$_1$. The LY$_1$ and HC$_1$ loci now meet the p' axis at 545 kPa and 218 kPa respectively. In the subsequent cooling-reheating cycles (2-3, 3-4, 4-5) the sample experiences only thermal elastic volumetric strains since the consolidation path intersects neither the TY$_1$ nor the LY$_1$ yield loci. From 5 to 6, the sample is mechanically loaded to p' = 500 kPa, but does not reach the LY$_1$ yield locus so just elastic strain is expected. Then, the sample is mechanically unloaded to p' = 200 kPa, implying an apparent OCR = 2.7 due to the shift in LY$_0$ (6-7). This will give rise to elastic rebound. It is also expected that the sample will experience only thermal elastic strains during the thermal cycle from 22°C to 100°C at p' = 200 kPa (7-8, 8-9, 9-10) because the path remains well under TY$_1$ and LY$_1$ (Figure 2a). The predicted variation of volumetric strain with temperature is compared with the experimental values in Figure 2b. It can be seen from both graphs that the predicted volumetric strains during thermal cycles are in good agreement with the experimental data. The mechanical volumetric strains, during loading from 400 kPa to 500 kPa and unloading to 200 kPa (5-6, 6-7) at 22°C, are also in good agreement with the observations.

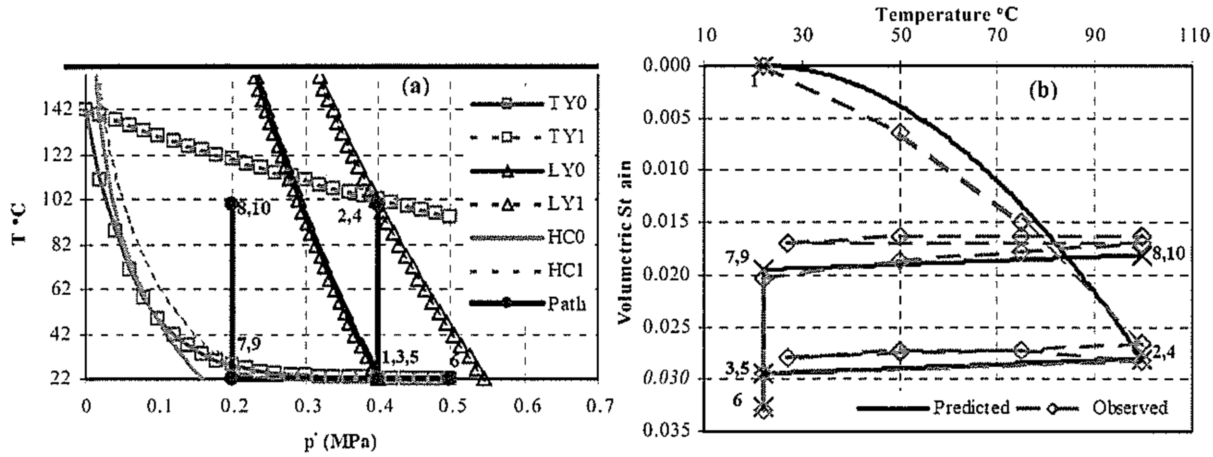

Figure 2. (a) Thermo-mechanical paths for Test 17 (OCR = 2.5), and (b) observed and predicted variations of volumetric strain with temperature

From the two experiments discussed here, it can be seen that Cui et al's model can qualitatively reproduce the expansion-contraction behaviour seen in test 14 and the trends in behaviour with OCR seen in the current study, and reported from many other studies (e.g. Baldi et al, 1991). However, it significantly underestimates the expansive thermal volumetric strains of the highly over-consolidated sample test 14 (OCR = 7). The model assumes that at high OCRs the expansive thermal volumetric strains are mainly elastic and a direct result of thermal expansion of soil particles, even when a sample is heated for the first time. The model also slightly under estimated the thermal expansion of the lightly OC sample, test 17 (OCR = 2.5), when it was heated for the first time (from points 7-8, Figure 2). The model reasonably predicts the volumetric strains during drained heating and cooling of NC samples. The volumetric strains at 50°C and 75°C lie above the predicted curve (Figure 2b) because the exponential curve (equation 8) assumed for the thermal plastic volumetric strain of NC samples appears to be slightly different from the observed thermal compression curve. Burghignoli et al (2000) have reported that the expansion observed in tests 14 and 17 when heating OC soils is not seen if the samples have been mechanically reloaded from a lower stress before heating. Consideration of all these observations indicates that there are significant limitations to the ability of the model to correctly predict the thermal strains of over-consolidated samples, but further experimental data are required to improve an understanding of this.

## DEVIATORIC STRESS-STRAIN RESPONSE

Typical experimental results from undrained tests on NC samples of M44 clay are compared with the corresponding output of the model in Figure 3. In the figures, the deviator stress, q, and pore pressure changes, Au, have been normalized by $p'_c$, the mean effective stress at the end of thermo-mechanical consolidation, and OB, and CC indicate observation, and prediction respectively. As can be seen in Figure 3, the predictions show a reduction in deviator stress, and hence shear strength, with increase in temperature, but this is less than observed. The initial slopes of the predicted curves are the same because Poisson's ratio has been taken as constant at all temperatures. The observed behaviour diverges significantly from the predictions between normalized deviator stresses of 0.3 and 0.5, suggesting that the elliptical shape of the yield locus is not correct for this clay.

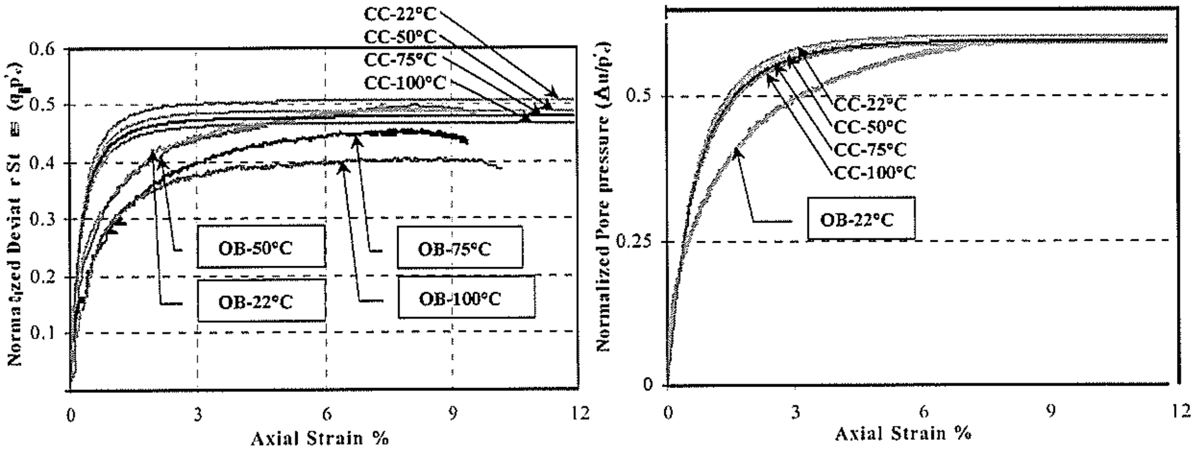

Figure 3. Observed and predicted undrained stress-strain response of NC samples of M44 clay

The observed development of pore pressure during undrained shear tests was practically independent of temperature, and only a single curve representing the observed behaviour at all temperatures is shown on Figure 3b. As shown in Figure 3b, the model also indicates only a minor reduction in the maximum pore pressure with temperature. Like the normalized deviator stress responses, the predicted pore pressure curves rise more steeply than the observed response, although the peak pore pressure has been correctly estimated.

Lightly over-consolidated samples have shown reductions in the undrained shear strength with increase in temperature, similar to the NC samples. The predictions for the over-consolidated samples significantly overestimate the maximum deviator stresses. Although the Modified Cam Clay model is known to give poor predictions for deviatoric loading of OC samples, the ultimate strength is usually reasonably well predicted. It can be shown that the poor predictions here are mainly a consequence of the assumed fixed separation of the INCL and CSL lines.

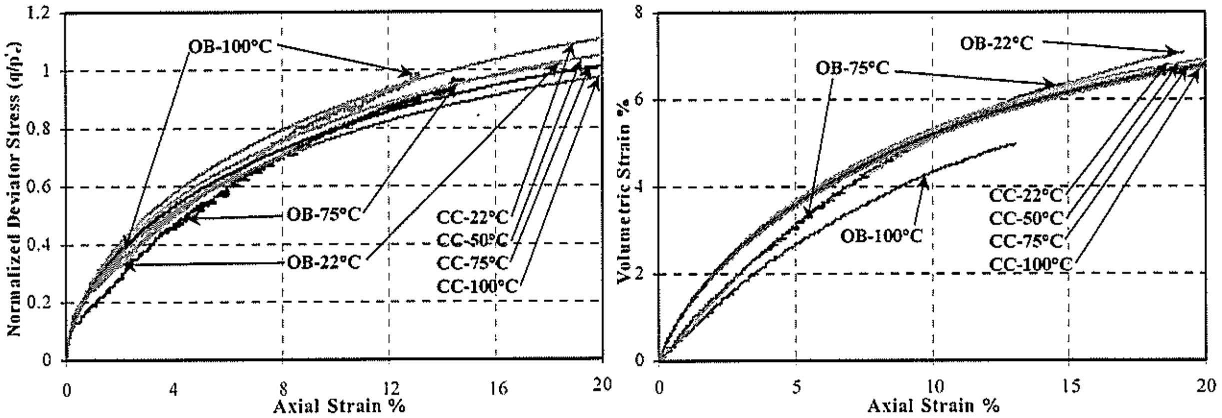

Figure 4. Observed and predicted drained stress-strain behaviour of NC samples at different temperatures

The behaviour of M44 clay during drained shear tests of NC samples has also been simulated and the results are demonstrated in Figure 4. The model predicts a reduction in shear strength with heating because of the reduction in M and a slight reduction in volumetric strain. Due to the limited experimental data, it is not clear whether the strength increases or decreases with increase in temperature, but at high temperature both axial and volumetric strains are less than those at room temperature, indicating a less ductile response. The reduction in ductility with temperature shown in Figure 4 has been observed also for Kaolin C1C. To produce the observed behaviour, the shape of the yield locus needs to change slightly with increasing temperature.

## SUMMARY

A recently developed thermo-mechanical model has been used to predict the responses observed in a series of experiments on an illitic clay, M44. The model, like many others that have been proposed to describe the thermo-mechanical behaviour, is a version of the Modified Cam-Clay model revised to include the soil response to temperature variation. Overall, the model gave reasonable predictions of the observed data. The reliability of the quantitative predictions decreased as the over-consolidation ratio increased, both for the thermal strains and for the deviatoric stress-strain response. Further data on the response of OC samples to heating and cooling are required to justify further model development. This should lead to greater understanding and the selection of more physically meaningful parameters.

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