

CHAPTER

1

INTRODUCTION

1.1 Background and methodology

In the last few decades, the effects of temperature on soil properties have become of more interest in the field of Geotechnical engineering. The main reason has been industrialization and the growing number of nuclear facilities for power generation. Thick formations of clay that provide low-permeability barriers have been proposed to host the disposal of high-level nuclear waste (used nuclear fuel) often at several hundred metres underground. The heat flow generated by nuclear waste or any other high temperature source, such as high voltage cables and heat storages, must be dissipated in the surrounding clay. This can significantly affect the physical, chemical and mechanical properties of clay in a way that can lead to fracture and the escape of radionuclides, or failure of foundations. Therefore, the effects of temperature on soil, and particularly on clay properties and behaviour, are of great importance.

Among the first studies in this area, Campanella and Mitchell (1968) investigated the thermally induced volume and pore pressure changes of an Illitic clay at temperatures up to 60°C. They provided a simple mathematical approach to determine the volumetric and pore pressure changes at elevated temperature. Since then thermal deformation of soil has been the subject of many studies. Habibagahi (1977) also looked into the effects of heating on the permeability of clay, as determined from consolidation curves. He concluded that permeability increased with increase in temperature as a result of the reduction in the viscosity of pore water, while absolute permeability remained dependant only on void ratio. Since 1980 a great number of thermo-mechanical models

have been developed by different researchers to simulate the soil behaviour at elevated temperature. They are mainly based on the elastoplastic model of modified Cam-Clay (Roscoe and Burland, 1968) and the critical state concept. The validity and applicability of these models needs to be examined by reliable experimental data as most of them have been developed in the absence of such data, and with many assumptions that may not reflect reality.

The thermo-mechanical behaviour of clay has been studied in Australia, by Chiu (1996), who investigated the effects of temperature on the behaviour of normally consolidated samples of kaolin at Sydney University. His results did not lead to a clear and reliable understanding of the effects of temperature on volume change, pore pressure, and shear strength partly because of the low thermal sensitivity of kaolin and partly because of difficulties with the calibration and operation of the high temperature triaxial apparatus (HTTA). Chiu (1996) made attempts to measure axial and radial displacements of his samples directly using proximity gauges, but these were unsuccessful due to their limited working range, inappropriate calibration and malfunctioning. In the past internal displacement measuring devices have not successfully been used for soft soils at elevated temperature due to technological difficulties. However, such measurements are needed if the influence of heating on the deformations is to be reliably obtained.

It is not clear whether the shear strength of soil increases or decreases with temperature. Efforts were made by Kuntiwattanakul et al (1995) to address these uncertainties. They related the observed controversies surrounding shear strength to the thermo-mechanical histories of the tested soils in various studies. Although this could explain some of the differences, the mechanism by which temperature affects the shear strength is still unknown. Permeability has been determined using indirect determinations from consolidation curves and very few studies have carried out direct permeability tests at elevated temperature. There are still many inconsistencies surrounding the thermo-mechanical behaviour of soil that need to be addressed by more experiments. From a soil mechanics viewpoint the current state of research is still far from providing a comprehensive understanding of heating effects on the mechanical properties of soil.

Attention in this research work is paid to improve the equipment and the methods of testing at elevated temperature to achieve more accurate and reliable results. It is also

intended to employ the critical state definitions to analyse the effects of heating on clay behaviour.

1.2 Objectives

The following objectives are pursued in this study:

- Select a clay that is more sensitive than Kaolin in order to get a more distinguishable response to changes in temperature. The mechanical behaviour of this clay should preferably be predictable by the modified Cam clay model.
- Modify the existing high temperature triaxial apparatus (HTTA, Chiu 1996) in order to:
 - 1- Measure the displacement of soil directly from on-sample instrumentation.
 - 2- Eliminate the problem of corrosion in the triaxial cell.
 - 3- Measure the axial load internally.
 - 4- Fully automate the operations of HTTA to provide continuous and remote monitoring and recording of the test results.
 - 5- Regulate the heat flow around the triaxial cell to have a uniform temperature gradient within the cell and the soil sample.
- Perform permeability tests, isotropic consolidated drained and undrained shear tests at elevated temperature on samples of the selected clays in order to investigate the effects of temperature variations on permeability, volumetric and pore pressure changes, shear strength, stress-strain response, Cam clay parameters and critical states.
- Implement a thermo-mechanical model to predict the thermal deformations and stress-strain response of clay samples for the purpose of comparison with the experimental results.

1.3 Outlines of dissertation

In Chapter 2 information from previous studies regarding the effects of temperature variations on the physical, chemical and mechanical properties of soil, such as thermal

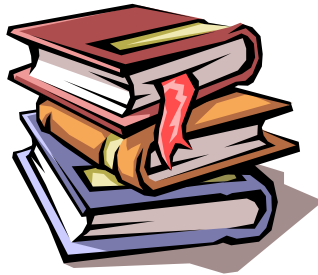
deformations and permeability are thoroughly discussed. Then the current state of thermo-mechanical modelling is reviewed and shortcomings are pointed out. The objectives for this research are explained.

In Chapter 3 details of the equipment used for both permeability and triaxial tests at elevated temperature are presented. Details of the programming for data acquisition, the calibration of the equipment, difficulties during testing, and sample preparation are discussed. Finally some recommendations are made for future improvements of the apparatus.

In Chapter 4 the results of permeability and triaxial compression tests at various temperatures (22, 50, 75, 100 °C) on two clays (M44 Illitic clay and Kaolin C1C clay) are analysed and reported in tabular and graphical forms. The critical state parameters are extracted and the locations of the isotropic normal consolidation line (INCL) and critical state line (CSL) in v - p' plane are estimated. Effects of temperature on the mechanical properties are discussed, comparing the results at room and elevated temperature.

In Chapter 5 the applicability of some of the thermo-mechanical soil models are investigated by using experimental results of M44 clay. For the purpose of comparison the thermo elastic-plastic model of Cui et al (2000) is implemented to predict the volumetric changes due to heating. The Cam clay model is used to simulate the stress-strain response of M44 clay during shearing. Finally the shortcomings of the models are discussed.

In Chapter 6 a summary of the preceding chapters is presented and the effects of temperature variation on soil properties from a soil mechanics viewpoint are discussed. Comments are made for future investigations in this area.



CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

In recent years 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. As the amount of fossil fuel resources in the world are decreasing the use of nuclear fuel for power stations is becoming more prevalent. 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. Figure 2.1 schematically shows the underground experimental facilities that were built for research on nuclear waste disposal at Mol, Belgium (operated by CEN/SCK Belgian Nuclear Energy Research Centre). 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. Geotechnical researchers have paid much more attention to the effects of temperature on soil properties in the last two decades, but there are still many uncertainties surrounding this subject. For example, the influence of temperature and thermo-mechanical consolidation path on soil strength is still controversial, and little data is available on the thermal expansivity of soils. What data there are, have been mainly obtained using external measuring devices and could be affected by measurement inaccuracies. To the author's knowledge just two studies have tried to use internal displacement measurement for soft soil at elevated temperature. Graham et al (2001) showed a view of internal displacement gauges used in their triaxial apparatus

but they have not presented any results from them. Chiu (1996) used internal proximity gauges for both lateral and axial displacement measurements, but they started malfunctioning and were difficult to calibrate. Several numerical and constitutive models have been developed to simulate the thermo-mechanical behaviour of soil, but their acceptability remain to be verified by increasing the accuracy and the number of experimental studies in this area. Above all, and most importantly from the soil mechanics viewpoint, the discrepancies among the findings of previous studies are mainly the result of the complex effects of temperature on soil-water interactions. These need to be addressed with more experiments at elevated temperature.

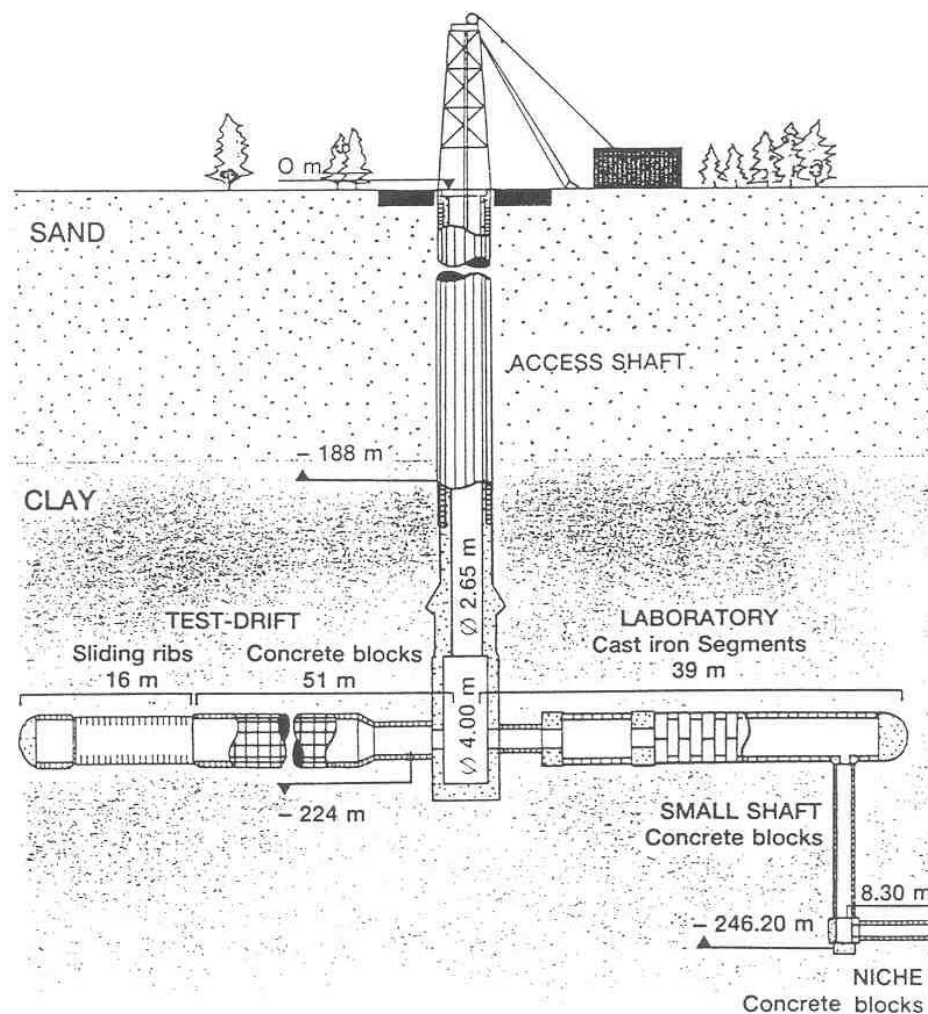


Figure 2.1 Schematic drawing of the nuclear disposal facility at Mol, Belgium (After Bath 1993)

In this chapter an overview of previous studies concerning the effects of elevated temperature on different properties of soil will be discussed, and the framework of the current study will be set. For experimental reasons the maximum temperature has been

limited to 100°C, and this review will mainly focus on the temperature range from 20°C to 100°C.

2.2 Background

Heating can significantly affect the physical, chemical and mechanical properties of soils in different ways that include: changing the properties of pore water; alteration of soil particles; and by affecting the soil-water system. The effects of temperature on different soil properties are discussed in the following sections.

2.2.1 Formation of new minerals

The removal of water and formation of new minerals occurs when soils are heated under atmospheric pressure (Wang et al 1990). Dehydration (removal of interstitial, absorbed and inter layer water) normally occurs at temperatures between 100°C and 200°C, while removal of hydroxyl ions will take place at temperatures between 500°C to 1000°C depending on the clay type. Towhata et al (1993a) performed scanning electron microscopy (SEM) on two dry clay powders, MC Kaolin and Bentonite, at temperatures between 20°C and 90°C and confirmed that there were no thermally induced changes in the appearance of clay. It has been reported by Seyfried and Thornton (1981) that Illite is partly replaced by Smectite at temperatures above 200°C when seawater is the pore fluid. In contrast, Weaver (1979) and Burst (1969) reported that Smectite gradually transforms to Illite with increasing depth and temperature when there is enough potassium in the sediment. Graham et al (1996) reported that an irreversible change (such as formation of new minerals) in Illite happens in the range between 100°C and 140°C. Therefore it appears that in the range from 20°C to 100°C neither new crystallization nor conversions of hydroxyl ions are expected.

2.2.2 Specific gravity

Some past studies have reported significant changes in the specific gravity of soil and water at elevated temperature. By heating two different clay powders (MC Kaolin and Western Bentonite) Wang et al (1990) showed that there was a sudden drop in the specific gravity of Kaolin at temperatures above 400°C but reported no major changes in the specific gravity of Western Bentonite at temperatures of up to 600°C. They suggested de-hydroxylation as the main cause for the reduction in Kaolin's specific

gravity. Figure 2.2 presents their results. Similar results (showing negligible changes in specific gravity with temperature) to the Bentonite have been reported for another Smectite clay, Wyoming Montmorillonite, for temperatures up to 1000°C (Grim 1968). It should be noted that the specific gravity in these studies was measured after cooling down to room temperature in a desiccator and their intention was only to investigate the permanent effects of temperature on soil specific gravity.

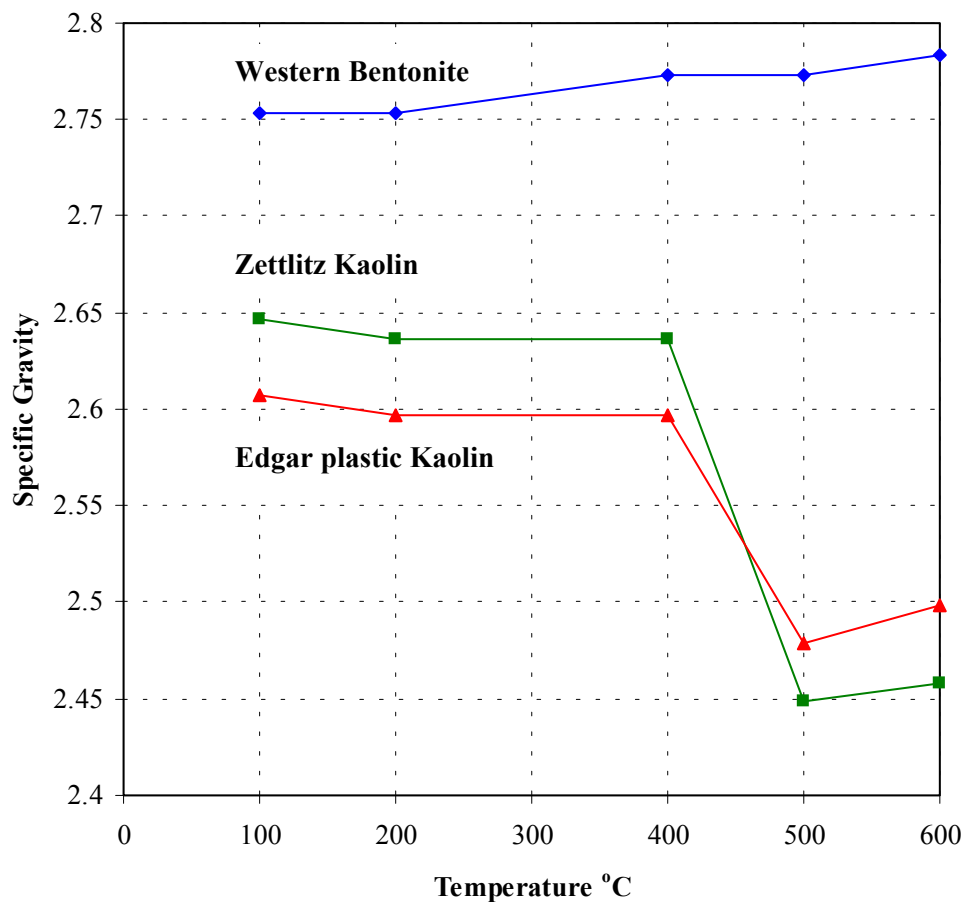


Figure 2.2 Variation of specific gravity of clay with temperature (after Wang et al 1990)

The water in the clay pores is in the forms of free water and bound water. The density of pore water varies from 1 Mg/m³ for free water to 1.41 Mg/m³ for the first layers of bound water at room temperature (De Wit and Arens 1950; Yong and Warkentin 1975). Therefore it might be important to know the states of pore water at various temperatures. Derjaguin et al (1986) has pointed out that the bound water properties approach those of free water as temperature rises and are identical to free water at

temperatures higher than 70°C. So at temperatures higher than 70°C all the pore water might be treated as free water. The changes in the density of free water are illustrated in Figure 2.3 (the data has been extracted from Perry's chemical engineer's handbook, 1997). As can be seen from the graph the density of water reduces from 0.998(~1) at 22°C to 0.958 at 100°C. During heating from 20°C to 100°C, the specific gravities (the ratio of γ_s/γ_w) at a particular temperature of most clays are expected to rise as the minor reduction in the density of clay due to thermal expansion of clay particles will be well overshadowed by reduction in the density of water. The consequent cooling to 20°C reduces the specific gravity to its initial value presenting a reversible phenomenon.

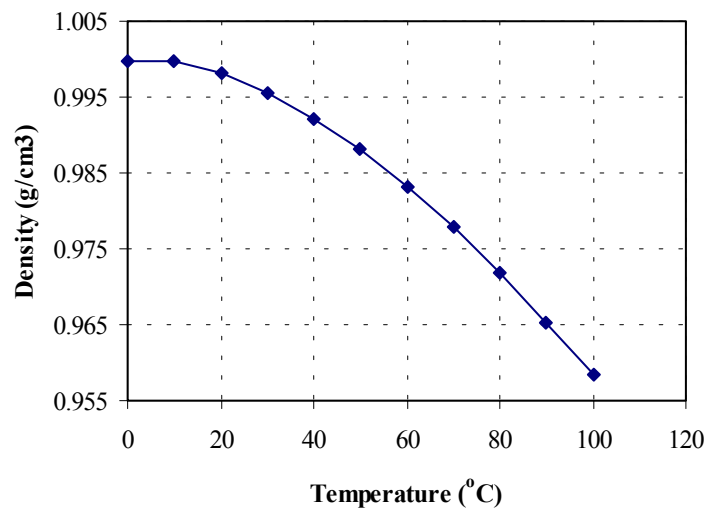


Figure 2.3 Changes in the density of water with temperature (Perry's chemical engineer's handbook, 1997)

2.2.3 Atterberg limits

It has been reported by many researchers, such as Beles and Stanculescu (1958), that changes in the Atterberg limits with temperature depend on the type of clay, and that temperature affects liquid limit (LL) and plasticity index (PI) more than plastic limit (PL). Soils with Bentonite as the dominant mineral show considerable reductions in LL and PI with heating, whereas the consistency indices of Kaolin based clays are less likely to change for temperatures up to 400°C (Wang et al 1990). Figure 2.4(a) and 2.4(b) illustrate the variations of the Atterberg limits with temperature for Bentonite and Kaolin respectively. It can be noticed from the graphs that for temperatures between 100°C and 200°C the effect of temperature is insignificant. Similar observations have been reported by Towhata et al (1993a) for temperatures in the range from 22°C to 200°C.

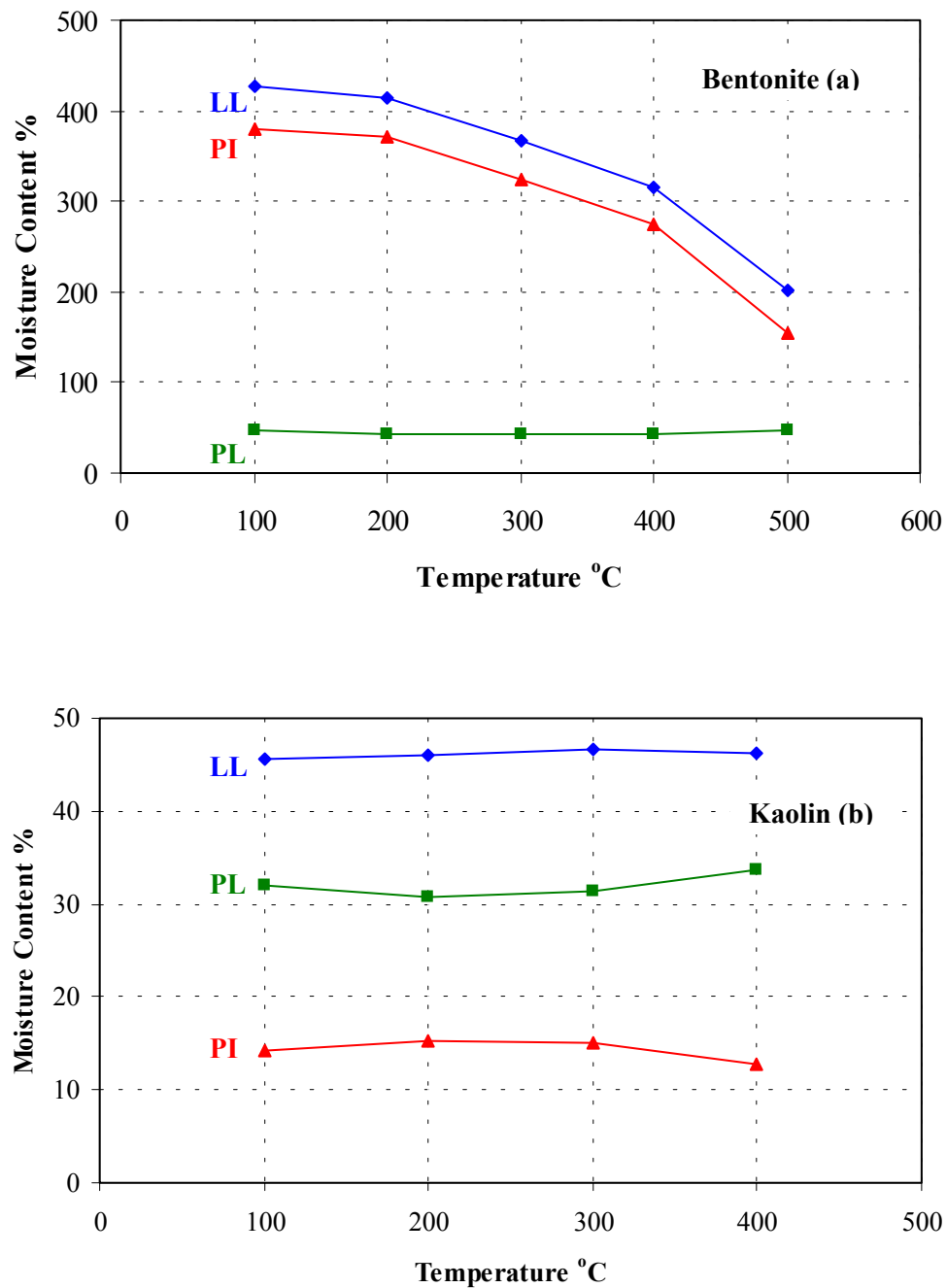


Figure 2.4 Variation of Atterberg limits with temperature (after Wang et al 1990)

In contrast, Yousef et al (1961) reported that the heating of clay from 14°C to 35°C resulted in a reduction in LL and PL. Towhata et al (1993a) noted that the clays they tested were previously subjected to a thermal cycle of up to 60°C during drying in the processing plant. This could be the case for most commercially manufactured clays, which are likely to have experienced similar procedures in processing. Jefferson (1994)

showed that LL of Kaolin clay slightly decreased with heating but Wyoming Bentonite (Sodium based) exhibited a dramatic increase in LL, which is in contrast with the findings of Wang et al (1990). Jefferson also suggested that the higher the thermal sensitivity of clay the greater the effects of temperature on the soil properties.

2.2.4 Thermal conductivity

The heat produced by high level nuclear wastes buried in clay barriers must be dissipated so the effect of temperature on thermal conductivity is an important issue. The thermal conductivity is a function of void ratio and increases as the void ratio and water content reduce. Morin and Silva (1984) used the standard needle probe method to determine the thermal conductivity of four types of sediments. Their results for Illite (from $e = 1.5$ to 2.6) and Smectite (from $e = 2.3$ to 4.8) showed that at constant temperature thermal conductivity increases with reduction in void ratio. For the purpose of comparison the results for Illite (LL = 95, PL = 43, SG = 2.78) and Smectite (LL = 270, PL = 91, SG = 2.74) at constant void ratios are compared with water's thermal conductivity at 60 MPa hydrostatic pressure in Figure 2.5.

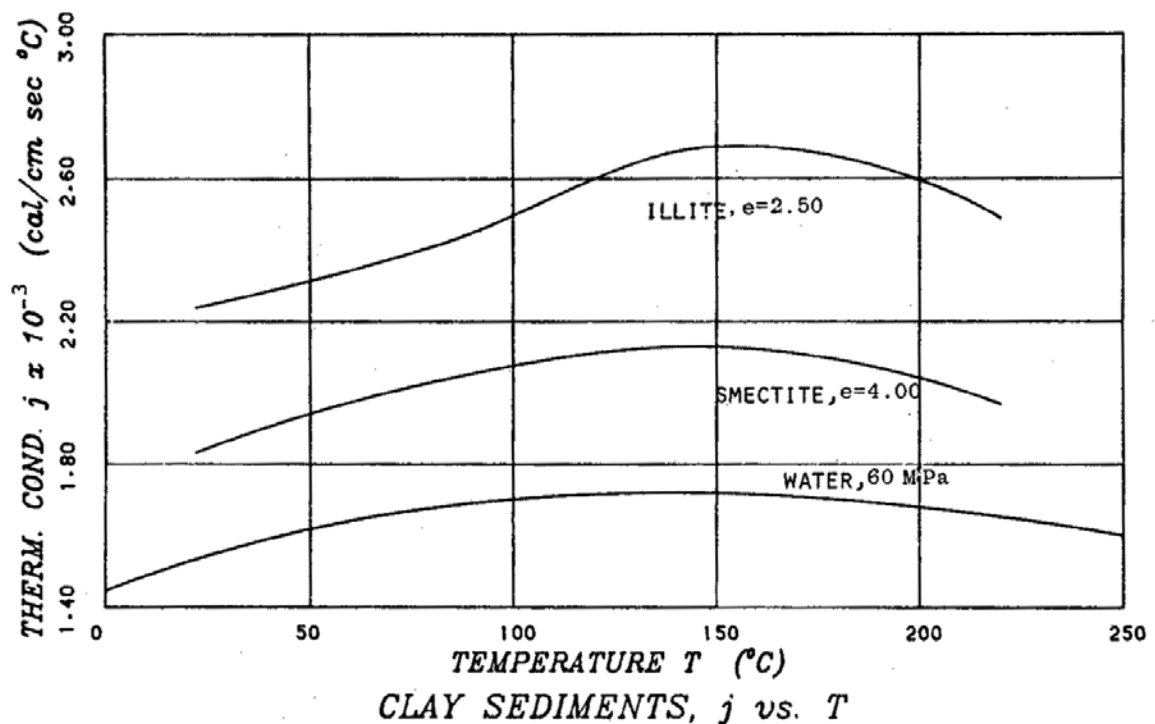


Figure 2.5 Variations of Thermal conductivity with temperatures (After Morin and Silva, 1984)

It can be seen from the graph that the behaviour of both clays is closely parallel to the water itself, but at a given temperature Illite has a higher thermal conductivity than Smectite as a result of having a lower void ratio. Considering their specific gravity, it can be noticed that the void ratios of 2.5 and 4 correspond to water contents of 90% and 146% for Illite and Smectite respectively. Also it seems that clay type has minor effects on thermal conductivity. Figure 2.5 shows that at constant void ratio the thermal conductivity increases with temperature up to a temperature of 150°C then starts to decline at higher temperatures. Morin and Silva (1984) suggested that this behaviour was purely a reflection of variations in the thermal conductivity of water (i.e. that the conductivity of the clay particles is unaffected by temperature).

2.2.5 Effects of heating on permeability of soil

Research into the effects of temperature on the permeability of soil, k , has been mainly based on indirect calculations from consolidation curves, and very few direct permeability measurements at elevated temperature have been carried out. Delage et al (2000) by performing constant head permeability tests on normally consolidated (NC) samples of Boom clay at temperatures between 20°C and 90°C showed that permeability increased with heating and reduced with increase in effective stress (reduction in porosity). Their results from isotropic consolidation tests indicated that for lightly overconsolidated ($OCR = 2$) samples, the value of C_v , the coefficient of consolidation, did not change significantly as a result of the simultaneous effects of reduction in porosity and increase in permeability with temperature increase. Delage et al (2000) showed that the determination of permeability at elevated temperature from consolidation curves could over estimate the permeability by a factor of approximately four in the case of Boom clay. The increase in permeability has been related to the decrease in the viscosity of pore water. Hillel (1980) has presented the following relationship for changes in the viscosity of water μ_w (in Pa.s) with changes in temperature T in °C:

$$\mu_w = -0.00046575 \ln(T) + 0.00239138 \quad (2.1)$$

Morin and Silva (1984), Habibagahi (1977), Houston and Lin (1987), Towhata et al (1993b) all have reported an increase in permeability at elevated temperature due to reduction in the viscosity of water. Among those only Morin and Silva (1984) performed constant head permeability tests in a rigid ring at temperatures ranging from

22°C to 220°C and hydrostatic pressure of 2 to 60 MPa on four types of sediments, of which two are of interest to the current study, Illite and Smectite. They found that the permeability is a function of void ratio and increases as the void ratio does, and at a given void ratio the permeability increases with temperature. They also indicated that the absolute or intrinsic permeabilities, $K_v = k\mu_w/\gamma_w$, of the tested sediments were only a function of void ratio and independent of temperature. These data (Morin and Silva) suggest a unique and linear relationship between void ratio and logarithm of intrinsic permeability independent from temperature and hydrostatic pressure. The location of this line is a function of plasticity index and at a given void ratio a more plastic soil will be more impermeable. Habibagahi (1977) also indicated the independence of absolute permeability from temperature variations by performing one dimensional consolidation tests on slightly organic clay.

The polarity and dipole moment of the permeating fluid can also affect the permeability (e.g. Lambe, 1954) by changing the thickness of the bound (double layer) water layer surrounding the clay particles. This double layer effect will be thoroughly discussed later in section 2.2.7. Most studies of the influence of temperature on permeability have predicted the same trend in the variations of permeability with temperature. However, relatively few direct permeability tests required for the proper determination of permeability, have been performed. More direct tests are required to confirm the independence of K_v from temperature, especially given the continuing controversy regarding effects of temperature on the double layer properties and thickness.

2.2.6 Volume and pore pressure changes

Changes in the volume of soil due to temperature variations have been the subject of many investigations since 1960. Heating under constant load can cause either contraction or expansion, and due to the low permeability rapid changes in temperature can lead to pore pressures being generated giving rise to thermal consolidation. Campanella and Mitchell (1968) performed isotropic compression tests on remoulded samples of Illite and San Francisco Bay mud at temperatures from 18°C to 60°C and effective stresses of up to 196 kPa. They observed that heating under drained conditions reduced the volume of saturated normally consolidated samples. The amount of volume change was not fully recovered in subsequent cooling and this irreversible volume deformation was related by Campanella and Mitchell to physico-chemical structural

changes in the clay. Similar observations have been reported by many other authors (e.g. Plum and Esrig 1969, Habibagahi 1977, Hueret et al 1988, Towhata et al 1993b and Burghignoli et al 2000). Campanella and Mitchell (1968) also showed that undrained heating of Illite samples (that had histories of drained thermal cycles) caused an increase in pore pressure, which was largely recovered upon cooling presenting a repeatable hysteresis loop in the v - p' plane (specific volume versus natural logarithm of mean effective stress). This hysteresis loop was not clearly identified in the samples of San Francisco Bay mud because they had not been subjected to previous drained thermal cycles, and instead a residual pore pressure build up (Figure 2.6) was noticed. They suggested that this residual pore pressure build up was the result of the same phenomenon, which is physico-chemical structural change. They observed that higher compressibilities caused lower temperature induced pore pressures, the compression index (the slope of normal consolidation line) was independent from temperature, and the normal compression curves in the v - p' plane for different temperatures were parallel. They have presented a mathematical approach (equations 2.2 and 2.3) to determine the volume change during drained heating and pore pressure change during undrained heating:

$$\varepsilon_v = \frac{(\Delta V_{dr} - (\alpha_w V_w + \alpha_s V_s) \Delta T)}{V} \quad (2.2)$$

$$\Delta u = \frac{n \Delta T (\alpha_s - \alpha_w) + \alpha_{st} \Delta T}{m_v} \quad (2.3)$$

where ε_v is the volumetric strain, ΔV_{dr} is the volume of expelled water during heating, α_w and α_s are cubical coefficients of thermal expansion of free water and soil particles respectively, α_{st} is physico-chemical coefficient of structural volume change, n is porosity, m_v is compressibility of soil structure, ΔT is change in temperature and V is initial volume of the sample.

There are some difficulties associated with the applications of these equations: Firstly, determination of the coefficient of volume compressibility (m_v) depends on the state of effective stress because the behaviour of samples during undrained heating-cooling cycles follows the rebound curve (Campanella and Mitchell, 1968). Secondly, the assumption that all the pore water is free water, water which is not associated with the clay particles, is not always true (Baldi et al 1988) and the properties of pore water may

differ from that of free water. All the pore water may be considered as free water only at temperatures higher than 70°C (Derjaguin et al, 1986). Finally, determination of displacements using external measurement devices does not seem to be accurate enough for calculations of the small volumetric strains (ϵ_v) caused by temperature change. For example, Campanella and Mitchell measured axial and volumetric strains by means of dial gauge and pipette respectively.

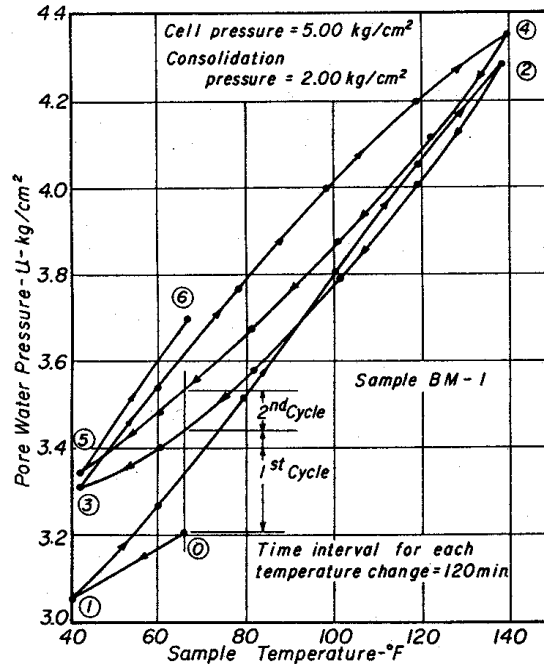


Figure 2.6 Thermally induced pore pressure changes of San Francisco Bay mud
(after Campanella and Mitchell, 1968)

Baldi et al (1988) have suggested that the free water prediction cannot be applied to all the pore water in low-porosity clays such as Pontida silty clay because the thermal expansion of bound pore water is significantly influenced by electro-chemical or electrical micro-structural interactions. They also presented an equation (2.4) for predictions of volumetric strains with temperature assuming there is no free water in dense plastic clays.

$$\epsilon_v = \frac{[\Delta V_{dr} - (V\Delta V_a S_s \rho_d + \alpha_s V_s)\Delta T]}{V} \quad (2.4)$$

Where: ΔV_a is the volume of expanded adsorbed water per unit surface area of clay mineral per °C and is equal to $(401.99+1.2897T) \times 10^{-4} \text{m}^3/\text{°C}$ for Boom clay, S_s is specific surface of the clay ($180 \text{m}^2/\text{g}$ for Boom clay), ρ_d is dry density ($19 \text{Mg}/\text{m}^3$, Boom clay) and α_s is 10^{-5}°C^{-1} for Boom clay.

The coefficient of thermal expansion of water, α_w , was considered to change with temperature and pressure, and was approximated by the following equation (Baldi et al, 1988):

$$\alpha_w(T, P) = \alpha_0 + (\alpha_1 + \beta_1 T) \ln(mp) + (\alpha_2 + \beta_2 T) (\ln(mp))^2 \quad (2.5)$$

They derived this equation from empirical values reported by Juza (1966) for the specific volume of water at various temperatures and pressures. The parameters are $\alpha_0 = 4.505 \times 10^{-4} \text{°C}^{-1}$, $\alpha_1 = 9.156 \times 10^{-5} \text{°C}^{-1}$, $\alpha_2 = 6.381 \times 10^{-6} \text{°C}^{-1}$, $\beta_1 = -1.2 \times 10^{-6} \text{°C}^{-2}$, $\beta_2 = -5.766 \times 10^{-8} \text{°C}^{-2}$, $m = 15 \text{MPa}^{-1}$. Equation 2.5 does not seem to be correct because with the above parameters it implies a different shape and trend from the Figure shown by Baldi et al (1988). Delage et al (2000) have examined both Campanella and Mitchell's and Baldi et al's approaches to evaluate heat induced volumetric deformations of normally and lightly over consolidated samples of Boom clay over the temperature range from 20°C to 100°C and for effective stresses of up to 4 MPa. They concluded that both predictions over-estimate the pore water expansion below 60°C, but if the effect of pore pressure and temperature on water's coefficient of thermal expansion is considered, the simple free water model of Campanella and Mitchell (1968) can satisfactorily predict the thermal expansion of pore water for Boom clay. The validity of this comment should be investigated for any higher plasticity or denser clay. Mortiz (1995) also showed that maximum thermally induced pore pressure in samples of Linköping clay in the range of 35°C to 70°C could be estimated from predictions of Campanella's model with good accuracy. Houston et al (1985) indicated that the thermally induced pore pressures are higher for samples with bigger initial temperatures. This would be expected because of the higher α_w at higher temperatures.

Baldi et al (1988) showed that over consolidated (OC) samples have different responses to temperature variations. Highly OC samples present expansion while lightly OC samples indicate contraction upon heating. Plum and Esrig (1969), and Graham et al (2001) have also shown that the volumetric strains depend on the stress level and temperature. On the other hand, Burghignoli et al (2000) demonstrated that if NC or OC

clay samples had a recent stress history of loading they would contract after heating, whereas OC samples with a recent history of unloading would expand. They suggested that the void ratio changes due to temperature changes depend on many factors including the stress history, thermal history, recent stress history, the elapsed time between the end of mechanical consolidation and the beginning of heating, and the duration of heating and constant temperature phases. The dependence of thermal deformation on the last three factors could be the result of the time dependent behaviour (creep) of their tested clays. The effects of temperature on creep will be discussed later in section 2.2.8. Burghignoli et al 's findings are similar to those of Towhata et al (1993b) who performed conventional oedometer tests on two types of clay (MC Kaolin and Bentonite) at temperatures ranging from 22°C to 90°C. They found that heating following mechanical loading or reloading causes a contraction independent of stress level and OCR, while the amount of thermal expansion following mechanical unloading depends on OCR. The thermal contraction responses of reloaded overconsolidated (OC) Kaolin samples are illustrated in Figure 2.7.

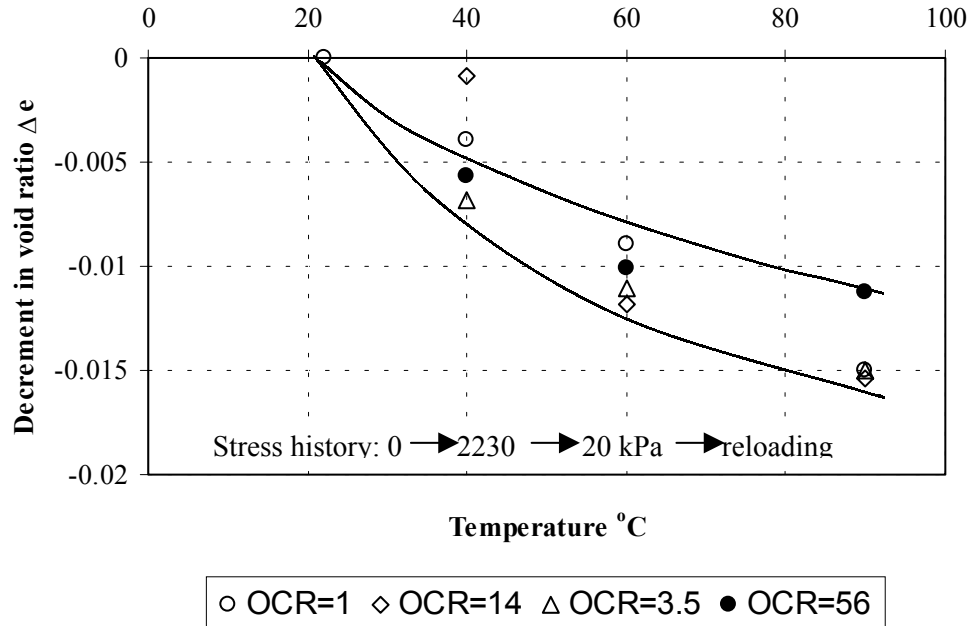


Figure 2.7 The variation in thermal compression of reloaded OC samples (after Towhata et al, 1993b)

It should be noted that a decrease in void ratio does not necessarily mean contraction because thermal expansion of the soil particles, α_s , also contributes to the change of

void ratio. The volumetric strain (ε_v) due to changes in temperature (ΔT) can be calculated from the following relationship which is not equal to $\Delta v/v_1$:

$$\varepsilon_v = (1 + \alpha_s \Delta T) \frac{v_2}{v_1} - 1 \neq \frac{v_2 - v_1}{v_1} \quad (2.6)$$

where v_2 and v_1 are specific volume of sample at temperatures T_2 and T_1 respectively.

From this equation (2.6) it can be seen that ε_v and $\Delta v/v_1$ can have different signs. Demars and Charles (1982) have investigated the effects of a thermal cycle (25°C-50°C-25°C) on the volume changes of NC and OC samples of five different soil types with different plasticities. They showed that the permanent decrease in void ratio due to temperature cycling, Δe_{st} , in any normally consolidated soil is unique and is independent of the magnitude of the effective confining stresses. They reported that Δe_{st} increases linearly with plasticity index (Figure 2.8) and could be determined from the following empirical relationship:

$$\Delta e_{st} = (0.00048 + 0.0000088PI)\Delta T \quad (2.7)$$

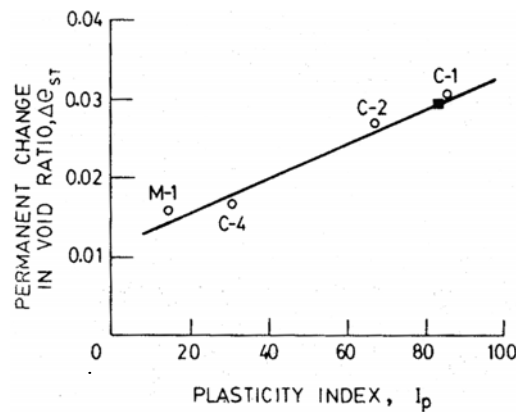


Figure 2.8 Changes in Δe_{st} with plasticity index (after Demars and Charles 1982)

So the higher the plasticity the more volume change due to a thermal cycle is expected. On the other hand, for over consolidated (OC) soils Δe_{st} depends on the soil type, plasticity and OCR. They indicated that Δe_{st} decreases with increasing OCR (Figure 2.9), and the maximum value of Δe_{st} during reloading of OC soils maybe considered constant. They finally inter-related these thermal deformations to the viscous behaviour of the solid skeleton. A similar study was carried out by Burghignoli et al (1992) on three types of clay with different plasticities in the range of 15°C-60°C. They also reported the dependence of Δe_{st} on the magnitude of the temperature cycle and soil

plasticity and its independence from stress level. In addition to the degree of over-consolidation (OCR), Δe_{st} also depends on the recent stress history. For example at OCR = 4, they noticed that if the sample had a recent history of unloading, Δe_{st} was negative (expansion), whereas a sample with a history of reloading showed positive Δe_{st} (contraction). The value of Δe_{st} reduces with an increase in the number of thermal cycles and the length of elapsed time from the end of mechanical consolidation to the start of the thermal cycle. They demonstrated that thermal load accelerates the mechanical creep and when they distinguished the permanent void ratio variations due to thermal cycle (Δe_{st}) from those created by mechanical creep (Δe_{cr}) alone, there was a linear relationship between them. Campanella and Mitchell (1968) indicated that a large number of thermal cycles will lead to thermal stabilization in the soil (i.e. $\Delta e_{st} = 0$).

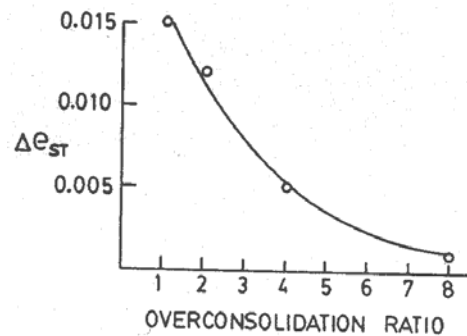


Figure 2.9 Changes in Δe_{st} with OCR (after Demars and Charles 1982)

Agar et al (1987) studied the thermal expansion behaviour of Athabasca oil sand over the temperature range from 20°C to 300°C using a high temperature triaxial machine and consolidometer. They reported non linear changes in pore pressure with temperature during undrained heating under constant total confining stress similar to other studies (e.g. Campanella & Mitchell 1968, Houston and Lin 1987, Tanaka 1996), but showed that under constant effective confining stresses pore pressure increased linearly with increase in temperature.

The coefficients of undrained (α_u) and drained (α_{dr}) thermal expansion can be used to describe the thermal expansion behaviour of clay. Chiu (1996) showed that the value of α_u for Kaolin C1C in the range of 22°C to 100°C was temperature dependant but was not significantly affected by stress level. On the other hand, it was observed by Tanaka and Graham (1996) during isotropic drained and undrained heating of reconstituted

Illitic shale at temperatures between 28°C and 100°C that α_u was independent of temperature and stress history. In contrast α_{dr} was dependent on both temperature and stress history. Tanaka et al (1996) also reported that the over-consolidation induced by temperature had a similar effect to that produced by mechanical over-consolidation.

The preconsolidation pressure decreases non-linearly with increase in temperature (Eriksson 1989, Tidfors and Sallfors 1989, Boudali et al 1994). They all carried out isothermal oedometer tests at elevated temperature on different types of clay. Tidfors and Sallfors (1989) claimed that clay contents, microstructure and water content are the three main parameters governing the effects of temperature on deformations of clay and concluded that the higher the liquid limit the greater the effects on preconsolidation properties. In addition to the effect of temperature on preconsolidation pressure, Boudali et al (1994) suggested that an increase in strain rate would also increase the pre-consolidation pressure.

In addition to the above effects of temperature on thermal deformations of soil, heating also causes a quasi-pre consolidation effect when mechanically loaded both after heating and after cooling (Campanella and Mitchell 1968, Plum and Esrig 1969, Towhata et al 1993b). The quasi-pre consolidation effect after a thermal cycle is removed by further mechanical loading.

2.2.7 Clay-water interaction

Thermally induced pore pressures and volume changes have been related to changes in the double layer thickness by many researchers. The diffused double layer or adsorbed water is described as a distribution of hydrated ions around the surface of clay particles due to electrostatic forces which tend to diffuse to a lower concentration in free water (Morin and Silva 1984). Plum and Esrig (1969), and Tidfors and Sallfors (1989) commented that the thickness of the double layer decreases with heating and leads to changes in the volume of free water and consequently thermal deformations under drained conditions. In contrast, Yong et al (1962) suggested a thicker double layer due to increase in temperature. The size of the double layer can be calculated from the following relationship (Van Olphen, 1977):

$$L_d = \left(\frac{d_i BT}{8\pi CS^2 V_c^2} \right)^{\frac{1}{2}} \quad (2.8)$$

where d_i is the dielectric constant of the pore fluid, B is Boltzman's constant, T is temperature, C is the electrolyte concentration, S is unit electronic charge and V_c is the cation valence. As the temperature increases the dielectric constant of water reduces. This behaviour is clearly shown in Figure 2.10. Mitchell (1976) believes that the reduction in d_i is counter balanced by the increase in temperature and for the range of 0°C to 60°C the change in double layer size (L_d) is not significant.

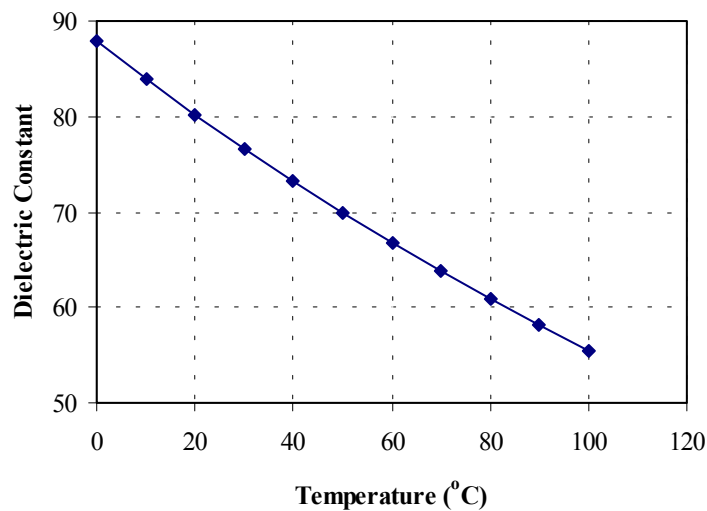


Figure 2.10 Variation of water's dielectric constant with temperature (Perry's handbook, 1997)

However Morin and Silva (1984) in agreement with Lawson and Hughes (1963) data on variations of dielectric constant with temperature suggested a 30 percent decrease in the resultant of $d_i T$ from 20°C to 200°C . Considering figure 2.10, in the range of 20°C to 100°C only about 11% reduction in $d_i T$ is expected. Heat also increases the solubility of minerals and accelerates chemical changes (Weaver 1979) so the ion concentration, C , increases. This together with a reduction of pH due to temperature increase leads to a greater reduction in the thickness of double layer. According to Van Olphen's (1977) double layer model a reduction in double layer thickness with heating is inevitable, but it is not certain that this can explain all the controversies around the thermally induced volume changes in clay. Morin and Silva (1984) suggested that in the low porosity region ($e < 1$) variations in double layer size might be more significant. Baldi et al (1988) believe that when the porosity is very low, the diffuse double layer theories are unable to predict the interaction forces. Towhata et al (1993b) also believed that physico-

chemical based theories such as diffuse double layer cannot explain the irreversible volume changes in the soil because they are based on reversible phenomena. They suggested that electrical polarization plays the main role. As a result of an increase in the kinetic energy of bound water due to heating its water molecules are more likely to overcome electrical attractive forces and become free water. This in turn reduces the thickness of the water layer and results in greater particle contacts. The decrease in water viscosity together with increase in free water accelerates seepage and volume changes. It was mentioned earlier that although the volume changes after a thermal cycle seem to be irreversible this only creates a quasi-pre consolidation effect which can be removed by further mechanical loading. Therefore, the stated reason by Towhata et al to reject the double layer based theories does not seem to be appropriate. It can also be considered that thermal agitation of the water molecules of bound water could cause the dissipation of water and result in thermal consolidation (Paaswell 1967).

The subject is still quite controversial, but earlier observations regarding the independency of absolute permeability (K_v) to temperature variation suggest that any physico-chemical effects are not significant.

2.2.8 Secondary consolidation or creep

There are many different opinions on the effects of temperature on creep or secondary consolidation. The coefficient of secondary consolidation, C_α , can be used for the purpose of comparison (equation 2.9).

$$C_\alpha = -\frac{\Delta e}{\Delta \log(t)} \quad (2.9)$$

Where Δe is the change in void ratio and $\Delta \log(t)$ is the change in the logarithm of time. Habibagahi (1977) and Mesri (1973) showed that C_α for both normally and overconsolidated samples of inorganic Paulding clay (LL = 54%, PI = 25%) and for normally consolidated organic Paulding clay (LL = 70%, PI = 25%) was independent of temperature, whereas for organic overconsolidated samples it increased with an increase in temperature. Plum and Esrig (1969) also reported that the secondary compression rates were only slightly affected by increase in temperature. Similarly, Chiu (1996) showed a slight reduction in the rate of creep at elevated temperature for Kaolin C1C, although it will be shown in chapter 3 that there are some uncertainties involved in his volume measurements due to leakage in the drainage system. On the other hand,

Campanella and Mitchell (1968), Houston et al (1985), Tidfors and Sallfors (1989), Burghignoli et al (1992), and Towhata et al (1993b) reported that elevated temperatures increased the rate of thermally enhanced secondary compression. An increase in creep might be expected because of the increase in the energy level (Tidfors and Sallfors, 1989) or because of bond breaking and structural rearrangements (Houston et al 1985). Burghignoli et al (1992,2000) indicated that elevated temperature accelerates mechanical creep and reported a linear relationship between permanent void ratio variation caused by a thermal cycle and void ratio changes due to creep as discussed previously. They suggested that the structural rearrangements due to temperature elevation are amplifications of those responsible for creep deformations. They proposed that the viscosity of the soil skeleton could contribute to the link between the thermal and time dependent behaviour of clayey soils. It would however be expected that any physical-chemical changes, for instance in the properties of the bound water, would produce additional effects to those caused by creep at room temperature.

Houston et al (1985) revealed that during undrained creep tests under constant deviatoric load the strain rate (% strain/time) decreases with increase in temperature. At constant temperature this strain rate initially decreases with increase in time but it may be followed by a sudden increase in the strain rate if the sample is headed towards creep rupture. The tendency for creep rupture increases at higher temperatures as a result of a greater reduction in effective stresses.

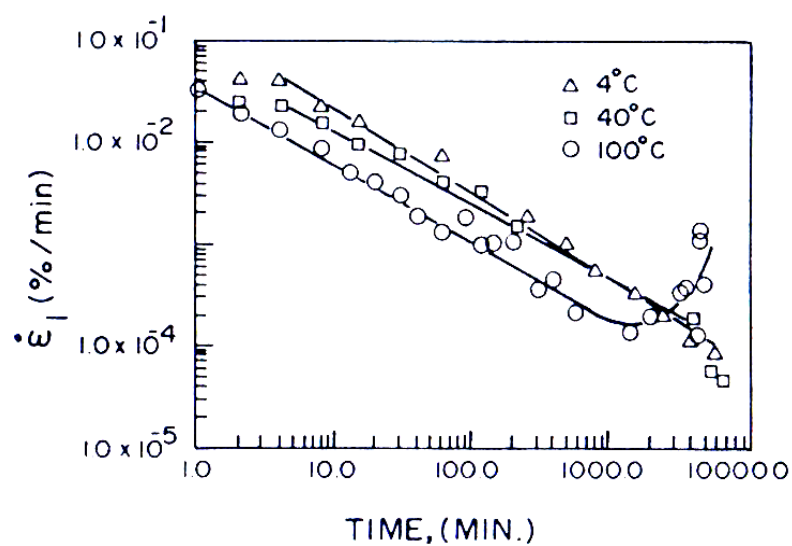


Figure 2.11 Undrained deviatoric creep response of undisturbed Pacific Illite (after Houston et al 1985)

The apparent inconsistency in the changes of creep rate due to heating might be explained by variations in the tested soil parameters such as liquid limit and plasticity. It may also be noted that there is no similar data to corroborate the results shown by Houston et al (1985).

2.2.9 Stiffness and shear strength

Despite the efforts made by Kuntiwattanakul et al (1995) to resolve the controversy, the influence of temperature on stiffness and shear strength remains unresolved. They have related the inconsistencies surrounding changes in the shear strength of soils at elevated temperature (e.g. strengthening and weakening after heating) reported by different researchers to differences in the consolidation history. Kuntiwattanakul et al (1995) could explain some of the differences but not all. Also they did not distinguish between the type of tests for the purpose of comparison. For example, Murrayama (1969), Sherif and Burrous (1969), and Laguros (1969) all carried out unconfined compression tests while others performed isotropically consolidated triaxial tests. Table 2.1 summarizes the results of many of the shear experiments that have been carried out on clay at elevated temperature. Murrayama (1969), Sherif and Burrous (1969), and Laguros (1969) claimed that undrained heating caused a reduction in undrained shear strength of different clayey samples during unconfined compression tests. The results of isotropic undrained triaxial tests in the range from 4°C to 200°C on two types of normally consolidated (NC) seafloor sediments (Illite and Smectite rich sediments, LL = 88%, PI = 47%) revealed that heating under drained conditions caused an increase in the subsequent undrained peak shear strength and stiffness. This was attributed to the extra volumetric strain during thermally induced consolidation (Houston et al 1985). Kuntiwattanakul et al (1995) reported similar results from isotropically consolidated undrained triaxial tests on NC and OC (overconsolidated) samples of MC Kaolin clay (LL = 70%, PI = 29%) in the range from 20°C to 90°C. Kuntiwattanakul et al (1995) indicated that the undrained shear strength and stiffness of NC samples heated under drained conditions increased with increase in temperature independent from consolidation path, whereas the undrained shear strength of OC samples was unaffected by heating and only the initial stiffness at (0.1% axial strain) increased with temperature. They also showed that the time allowed for mechanical consolidation (the time beyond the primary consolidation) at room temperature had no effect on

maximum undrained deviator stress reached, but the longer the consolidation period the greater the secant modulus at 0.1% strain.

Table 2.1 Review of temperature effects on shear strength of soils

Author	Soil	LL & PI	Temp. Range	Consolidation	Type of Shearing	Strength after Heating
Murrayama (1969)	Osaka clay			UH	UU	Down
Sherif & Burrous (1969)	Kaolin clay			UH	UU	Down
Laguros (1969)	3 clay types	29-47%		UH	UU	Down
Ctori (1989)	Brick clay		6-35°C		UU	Down
Towhata et al (1993b)	Kaolin & Bentonite	70%, 29%	Up to 200°C		UU	Unchanged
Nobel & Demirel (1969)	Iowa clay	89%, 59%				Down
Mitchell (1964)	San Francisco Bay mud			NC, DH	IU	Down
Houston et al (1985)	Illite Smectite	88%, 47%	4-200°C	NC, DH	IU	Up
Hueckel & Baldi (1990)	Pontida clay		18-115°C	OC, DH	ID	Down
Burghignoli et al (1992)	Todi clay	52%, 30%	15-60°C	NC, Cyclic DH	IU	Unchanged
Lingnau et al (1995)	Sand Bentonite	250%, 200%	26-100°C	NC, DH	IU	Down
Moritz (1995)	Linkoping clay	65-90%	Up to 70°C	NC, UH	IU	Down
Kuntiwattanukul et al (1995)	MC Kaolin	70%, 29%	20-90°C	NC, DH	IU	Up
				OC, DH	IU	Unchanged
Chiu (1996)	Kaolin C1C		22-100°C	NC, DH	IU	Unchanged
					ID	Up
Tanaka et al (1997)	Illitic shale	30%, 21%	28-100°C	NC, DH	IU	Down

*NC(normally consolidated) ,OC(overconsolidated), UH(undrained heating), DH(drained heating), UU(unconfined undrained), IU(isotropic undrained),ID(isotropic drained)

In contrast, Mitchell (1964) demonstrated that NC samples of San Francisco Bay mud presented lower undrained shear strength after drained heating. Lingnau et al (1995) carried out undrained triaxial tests on NC dense saturated sand-bentonite (Bentonite, $LL = 250$, $IP = 200$) at effective stresses up to 9 MPa and temperatures of 26°C, 65°C and 100°C. They also indicated that the shear strength reduces while the strength envelope increases in size with increase in temperature. They have related this apparent paradox to the higher pore pressure development at elevated temperature.

In agreement with Mitchell (1964) and Lingnau et al (1995), Tanaka (1997) concluded that the undrained shear strength decreased with an increase in temperature from 28°C to 100°C for a NC illitic shale ($LL = 30$, $PI = 21$) with a history of drained heating. There are some other results (i.e. Chiu 1996), which show that the undrained shear strength is unaffected by variations of temperature. Burghignoli et al (1992 and 2000) carried out isotropic constant rate of loading (CRL) and undrained triaxial compression test on remoulded samples of Todi clay ($LL = 52\%$, $PI = 30\%$) at temperatures ranging from 15°C to 60°C. They concluded that the strength envelope was independent of temperature and thermal history. The samples that had experienced drained thermal cycles presented higher stiffnesses but no changes in strength. For samples that had never experienced higher temperature than the current temperature the shear strength and stiffness did not significantly change whereas for samples with thermally induced over-consolidation (i.e. they had experienced higher temperatures than the current temperature) stiffness increased for a limited range of stress and strain increment. The increase in stiffness was related to quasi-preconsolidation phenomena similar to those produced by creep deformations. Towhata et al (1993b) also showed that the unconfined compression strengths of two types of clay, MC Kaolin clay and Bentonite were independent of temperature in the range of 28°C to 200°C and remained unchanged.

The results presented show discrepancies between the findings of different authors even when the same thermo-mechanical history has been followed. Some of the discrepancies can be explained with examination of the thermo-mechanical histories. For example, Moritz (1995) carried out undrained heating followed by an undrained triaxial shear test on natural samples of Linköping clay ($LL = 65\%$ to 90%). The reduction in shear strength in this case, and any other cases with similar thermal history, can be associated with the decrease in effective stress resulting from thermally induced pore pressures.

Unconfined compression tests on heated soil specimens under undrained conditions in all studies (e.g. Sherif and Burrous 1969) except for Towhata et al (1993b) resulted in lower shear strengths. By careful examination of Figure 2.12, extracted from Houston et al (1985), it can be noticed that the increase in strength is not obvious for temperatures in the range from 4°C to 100°C, and it only becomes clear for tests at 200°C. At 200°C a high peak shear strength at very low strain is followed by strain softening. As this behaviour is not observed at temperatures below 100°C, it might be suggested that the strengthening at 200°C could be the result of physico-chemical changes in the soil such as occur in Montmorillonite above 100°C (e.g. see Figure 2.4). The stress softening behaviour has been explained by sliding along a thin failure zone due to very low void ratio at 200°C (Houston et al, 1985). This softening has not been observed for a sample with a similar history but that had its temperature reduced from 200°C to 100°C before shearing. In this case the strength remained the same ~130 kPa. It is believed that the thermally induced reduction in void ratio from 100°C to 200°C should not be significant enough to cause such a change in the stress-strain response.

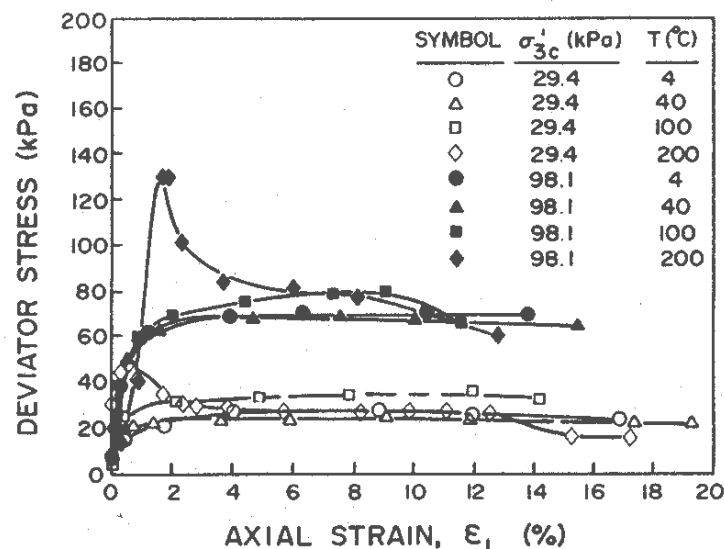


Figure 2.12 Stress-Strain path at different temperatures (after Houston et al 1985)

Hueckel and Baldi (1990) showed that the shear strength and stiffness of Pontida silty clay subjected to drained heating (18°C-115°C) reduced with increased temperature in isotropically consolidated drained triaxial compression tests. Jefferson et al (1996) related the above reduction in shear strength to reconsolidation of material in terms of fabric changes even though a small expansive strain was observed. Lack of

experimental data from drained triaxial compression tests of NC and OC soil samples prevents the clarification of this hypothesis. As pointed out by Jefferson et al (1996) anisotropy could have affected Kuntiwattanakul et al's (1995) results because they anisotropically consolidated the samples to 98 kPa before isotropic consolidation to 196 kPa in the triaxial cell. The effects of anisotropy and temperature were studied by De Bruyn and Thimus (1995). They conducted isotropically consolidated undrained triaxial tests on natural and reconstituted specimens of Boom clay at temperatures between 20°C and 80°C and confining pressures of 2.1 to 4.1 MPa. Three types of anisotropy were considered, insitu samples trimmed A) parallel to bedding planes, B) perpendicular to bedding planes and R) reconstituted samples. They demonstrated that the strength decreased from series A through series B to series R at a given temperature. The strength of series A and B clearly decreased with increase in temperature but series R showed some scatter in the results with no clear trend. It should be noted that all samples after saturation had been consolidated at room temperature under different effective stresses (presenting almost similar water contents and dry density at the end of consolidation in all three groups of A, B and R) before heating to different temperatures at which they were later sheared.

Wang et al (1990) investigated the effects of temperature on dry clay samples that were subsequently subjected to conventional triaxial tests. Samples of Kaolin powder were heated up to different temperatures in an oven and cooled down to room temperature. Then they were mixed with water, remoulded and triaxial compression tests were carried out at room temperature. They showed that under constant confining pressure the strength and initial tangent modulus were higher for room temperature samples than for those which their dry clay powder before moulding had experienced a thermal cycle of 22°C -100°C-22°C before being reconstituted. As noted previously most commercial clays will have been subjected to such a thermal cycle in their preparation. It follows that the effects of thermal cycles may be more significant for natural clays.

Overall, the previous studies show a trend for a reduction in undrained shear strength after samples are subjected to drained and undrained heating. In addition to the thermal history and mechanical consolidation history there appear to be other factors such as anisotropy and liquid limit that influence the temperature effects on the shear strength of soils (Kuntiwattanakul et al, 1995). As it was mentioned earlier in this chapter the liquid

limits of some clay types can change significantly with temperature. The current state of research cannot explain the mechanisms by which temperature affects the shear behaviour of soils. More experimental work in this area is necessary to resolve the uncertainties surrounding this subject.

2.2.10 Critical state and Cam-clay parameters

Samples under deviatoric load eventually tend to move to an ultimate state at which plastic shearing can continue indefinitely without changes in volume or effective stress. This condition of perfect plasticity is called a critical state (Wood 1990). Modified Cam clay (Roscoe and Burland, 1968) is an elastic-plastic constitutive model based on the critical state concept to predict the soil behaviour (especially clays) subjected to any type of loading. The model requires elastic properties, a yield surface, a plastic potential and a hardening rule. This model can be easily implemented knowing the soil parameters of M , λ , κ or K , N , and G or μ . Where M is the slope of critical state line (CSL) in q - p' plane, λ is the slope of isotropic normally consolidation line (INCL) in v - p' plane, κ is the slope of swelling or unloading line, K is the bulk modulus, N is a soil constant specifying the location of INCL in the v - p' plane, G is shear modulus, μ is the Poisson's ratio and v is specific volume.

The effects of temperature on soil parameters have been discussed by many studies in the past. It has been shown that the slope (λ) of the isotropic normal consolidation line (INCL) in v - p' plane is independent of temperature (Campanella and Mitchell 1968, Houston et al 1985, Kuntiwattanakul et al 1995, Lingnau et al 1995, Graham et al 2001) but an increase in temperature causes a parallel shift in the INCL to lower values of v at any given p' (lower N). Nearly all studies have confirmed this result. Campanella and Mitchell (1968), and Despax (1976) observed a slight reduction in the slope of the unloading line (κ) with temperature, whereas Lingnau et al (1995) and Tanaka et al (1996) suggested an increase in κ with temperature. As κ is influenced by effective stress (Campanella & Mitchell 1968) so, the assumption of constant κ in simple models is always involved with some error. Despax (1976) demonstrated that heating could cause a reduction in M , the frictional property. In contrast Hueckel and Baldi (1990), Houston et al (1985) and Graham et al (2001) observed that the strength envelope was independent of temperature, and therefore M . Lingnau et al (1995) showed that the

strength envelope was not linear and grew in size with increase in temperature for Sand-Bentonite samples. They also indicated that the extent of the pre-yield behaviour or elastic region shrunk with heating similar to Hueckel and Baldi (1990), Tanaka et al (1997) and Graham et al (2001). It has been considered by both Graham et al (2001) and Tanaka et al (1997) that shear modulus (G) and bulk modulus (K) decrease with temperature, but Tanaka et al believe that K/p'_c is independent of temperature while Poisson's ratio (μ) increases with temperature.

2.3 Modelling aspects

Mathematical and constitutive models have been developed by many researchers such as Hueckel and Baldi (1990) in order to investigate the thermo-mechanical behaviour of soils. These models are mainly extensions of the Modified Cam-clay model proposed by Roscoe and Burland (1968). Campanella and Mitchell (1968) proposed a mathematical approach to predict thermally induced volume change and pore pressure in the soil. Baldi et al (1988) showed that the assumption of free water made by Campanella and Mitchell was not representing the reality for low porosity Pontida silty clay. They noticed that plastic thermal contractions of normally consolidated (NC) clays were gradually converted to expansion at higher OCRs. Since then attempts have been made to include this phenomena. Hueckel and Borsetto (1990) were among the first researchers who proposed an extension to elastoplastic Cam-clay model using Prager's thermo-plasticity theory. A quantitative validation of this model was made by Hueckel and Baldi (1990). The non-linear reduction in preconsolidation pressure induced by heating (Eriksson 1989) was used to define a yield locus in the T - p' plane. The elastic region was considered to shrink with increase in temperature (thermal softening) and dilate during cooling. Plastic strain hardening and thermal softening occur simultaneously in the plastic state. NC and OC states were separately handled by thermo-plasticity and thermo-elasticity respectively in their model.

Britto et al (1989) proposed an elastic numerical approach to investigate the effects of temperature on consolidation around hot cylinders. They assumed that heating induced thermal stress and strains in soil but had no direct effect on work hardening. Seneviratne et al (1993) examined the models proposed by Britto et al (1989) and Hueckel and Borsetto (1990). They compared the test results on normally consolidated and lightly over consolidated samples and concluded that both models provide reasonable

predictions under isotropic stress conditions. Modaressi and Laloui (1997) proposed a thermo-viscoplastic constitutive model by introducing viscosity effects into a thermo-mechanical model. The model includes thermal hardening and the evolution of yield surface. The Mohr-Coulomb criteria were used to define the deviatoric yield surface. They compared their model with Cam-clay based models and suggested that the model was more capable of reproducing the experimental results. Tanaka et al (1996,1997) and Graham et al (2001) also proposed a thermoelastic-plastic model (TEP) more or less within the same frame work of Cam-clay in order to qualitatively predict heating, and cooling effects on volume changes, pore water pressure and strength of both normally and over consolidated specimens. They explicitly studied the effects of heating on yield loci and confirmed the findings of Hueckel and Baldi (1990) in which the elastic domain shrunk during heating and expanded upon cooling. To account for the dependency of volumetric strain on OCR they suggested that the slope of swelling line (κ) increased with increase in temperature. Like others, they also assumed that λ was independent of temperature and the INCLs were shifted to lower locations in v - p' plane with increasing temperature, although their experimental results on an Illitic clay were not convincingly indicating this phenomena. The strength envelope was considered to be independent of temperature, but an increase in temperature increased the shear strength. The normality condition (similar to Cam-clay) was considered so the strain tensor was assumed to be normal to the yield locus. Finally the undrained volumetric coefficient of thermal expansion (α_u) was considered constant ($2 \times 10^{-4} \text{ } ^\circ\text{C}^{-1}$ for Illitic clay). This assumption is surprising as the volume expansion of water is greatly influenced by temperature. Also Chiu (1996) showed that α_u was temperature dependant for Kaolin C1C. There are some shortcomings within their results for example their model could not predict the reduction in shear strength in the reported CIU test. Cui et al (2000) presented a new volumetric thermal plastic mechanism which allows for the prediction of plastic strains at higher OCR and simulates the over-consolidation effect due to heating of NC soils. They suggested a few additions to extend the Cam clay model (Hueckel and Borsetto 1990) and made one more assumption in which heating causes over-consolidation in NC samples under constant load. It is noteworthy that one of the key assumptions of nearly all models mentioned here, the conversion of thermally induced volumetric contraction of NC samples to expansion at higher OCRs, may not be always true. As discussed earlier in this chapter

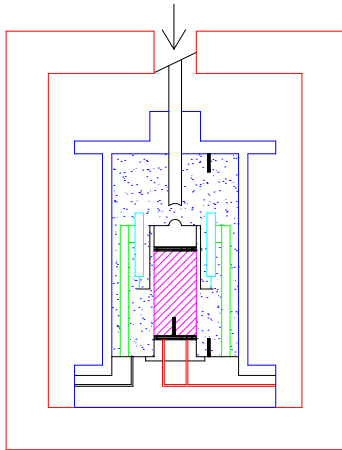
Burghignoli et al (2000) showed that the recent stress history must be considered as a major factor because NC or OC samples with a recent stress history of loading or reloading indicated volume contraction upon heating even at high OCRs.

2.4 Setting the objectives

Despite the greater attention to the thermo-mechanical behaviour of soils in recent years, the subject has not been fully understood yet. It has been shown in the literature that the effects of temperature on permeability have been investigated using mainly the consolidation curve, and only very few studies have conducted direct permeability tests. Due to technical problems at elevated temperature, thermally induced displacements have been determined in nearly all studies to date using external measuring devices and this could have led to significant errors in the predictions of soil stiffness, stress-strain response, and axial and volumetric strains during drained and undrained heating. The need for high temperature internal displacement measuring devices is felt more than before in order to firstly eliminate the errors and examine the validity of the externally measured axial and volumetric strains, and secondly to gain a clearer understanding of the thermal expansions of water and soil particles especially during undrained heating. The effects of temperature on shear strength are not fully understood. Further experimental works together with consideration of some other parameters in addition to the thermo-mechanical consolidation history such as a soil's thermal sensitivity and liquid limit could result in a better understanding of how temperature affects the shear strength of soils. This review of the current state of thermo-mechanical modelling of soil reveals that the models that have been developed are based on limited experimental data and on assumptions that may not be true, for example considering the slope of CSL in q - p' plane (M) as a constant. In some cases they have employed physically meaningless parameters in order to simulate the complex behaviour of soil at elevated temperature. Nevertheless a simple model based on the critical state concept such as Cam-clay with some modifications for temperature effects appears to be the best approach to predict the thermo-mechanical response of soil.

Considering the above facts it can be concluded that the current state of research on the behaviour of soils at elevated temperature is still far from complete and there are still many uncertainties that need to be addressed with more reliable experimental data at elevated temperature. In this study attempts are made to improve the experimental

techniques and the equipment needed for permeability and triaxial tests at elevated temperature. Then by performing constant head permeability tests, isotropic consolidation and shear tests on remoulded samples of two types of clay at various temperatures, the effect of heating on permeability, drained and undrained volumetric deformations, stress-strain response and critical state parameters are investigated. Finally the validity of one of the most recent and complex elasto-plastic thermo-mechanical models (Cui et al 2000) in association with the Cam clay model is critically examined using the experimental data from the current study.



CHAPTER 3

APPARATUS AND INSTRUMENTATION

3.1 Introduction

Normal soil laboratory equipment is not capable of performing tests at elevated temperatures above 50°C and special apparatus are essential for this purpose. In order to investigate the thermo-mechanical behaviour of clay a high temperature triaxial apparatus, the HTTA, was utilized. It had been previously designed and manufactured at the University of Sydney by Chiu (1996). The design of the HTTA was completely reconsidered and substantial modifications were carried out. The use of internal displacement transducers was one of the biggest challenges in this research. In this chapter the details of the equipment, the data acquisition system, calibration and the difficulties during testing are discussed.

3.2 Equipment and Experimental Setup

3.2.1 Hydraulic conductivity

Experiments to determine the permeability of clay were carried out when the author was waiting for parts of the HTTA to be made. A conventional triaxial cell was modified for use in the permeability tests. The general layout of the system is schematically shown in Figure 3.1. The setup consists of a triaxial chamber, temperature controlled oven, three GDS pressure controller units, a differential pore pressure transducer (DPPT), a standard pore pressure transducer (PPT), cell fluid (water), water container, thermocouples and finally a personal computer equipped with data acquisition boards. The triaxial cell was a standard Perspex type that could be safely used for temperatures up to 50°C. Draining from the top and bottom of the sample occurred through copper

tubes to two GDS pressure controllers. The pressure controllers were used to apply a nominally constant differential pressure of 20 kPa and to measure the flow of water. A differential pore pressure transducer (DPPT) was used to provide a more accurate measurement of the pressure difference between the top and the bottom. A third pressure controller was used to apply a cell pressure which acted all around the sample.

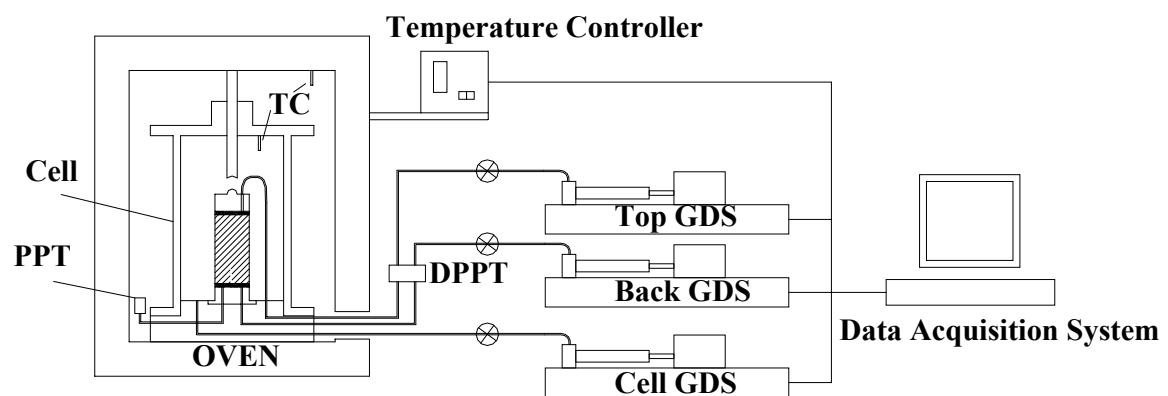


Figure 3.1 Schematic layout of permeability test equipment

The pore pressure at the bottom of the sample was determined by a PPT connected to the triaxial cell base. During the test, the triaxial cell was placed in a temperature-controlled oven and the temperature at all times was monitored by two K-type thermocouples (TC). The whole system, including the oven and all electronic devices, was connected to a data acquisition system (personal computer) for automatic control and monitoring.

3.2.2 Setup for triaxial testing

3.2.2.1 Room temperature triaxial apparatus

Before completion of the fully automated high temperature triaxial apparatus, some room temperature tests were carried out using a conventional triaxial machine. A

schematic layout of the system is shown in Figure 3.2a. The two GDS Pressure controllers regulate the pressure and volume change of water in the cell and in the sample. For a more accurate measurement of pore pressure a pore pressure transducer (PPT) has been attached to the bottom of triaxial cell. Deviatoric load is applied by a loading frame and is measured by both an external strain gauged proving ring and a 5kN internal load cell. A Linear Variable Potentiometer Transformer (LVPT) measures the axial displacement during the tests. The data acquisition system is fully automated and operated by a personal computer.

3.2.2.2 High temperature triaxial apparatus

The high temperature triaxial apparatus has been designed in the University of Sydney at the Centre for Geotechnical Research (CGR) by Chiu (1996). At the beginning of this research, the HTTA was found to need modification before starting triaxial testing at elevated temperature. The equipment was completely dismantled and modified to fulfil the requirements of this research. A schematic diagram of the new fully automated high temperature triaxial apparatus (FHTTA) is shown in Figure 3.2b.

Tests are carried out in a steel triaxial cell (Figure 3.2b) placed in a temperature-controlled oven. The oven's temperature is controlled using a K type thermocouple and a temperature controller unit (REX-D400) that are connected to the data acquisition system (DAS) through a RKC Com104C interface. The deviatoric load is applied by a 50kN loading frame and is measured by a strain gauged proving ring outside the oven (see Figure 3.2b). During tests, the sample's temperature is monitored and measured by means of 3 K type thermocouples mounted inside the triaxial cell.

Back pressure and cell pressure are applied by two standard GDS pressure controllers and for a more reliable measurement of pore pressure, a pore pressure transducer (PPT) has been located in the base of the triaxial cell inside the oven.

Two internal LVDTs (Linear Variable Differential Transducer), an external LVPT (Linear Variable Potentiometer Transformer) and two proximity gauges (PG) are responsible for the measurements of a sample's axial and radial displacements. The internal LVDTs and PGs have been mounted on a ceramic stand with a relatively small coefficient of thermal expansion to minimise corrections due to thermal strains of the apparatus.

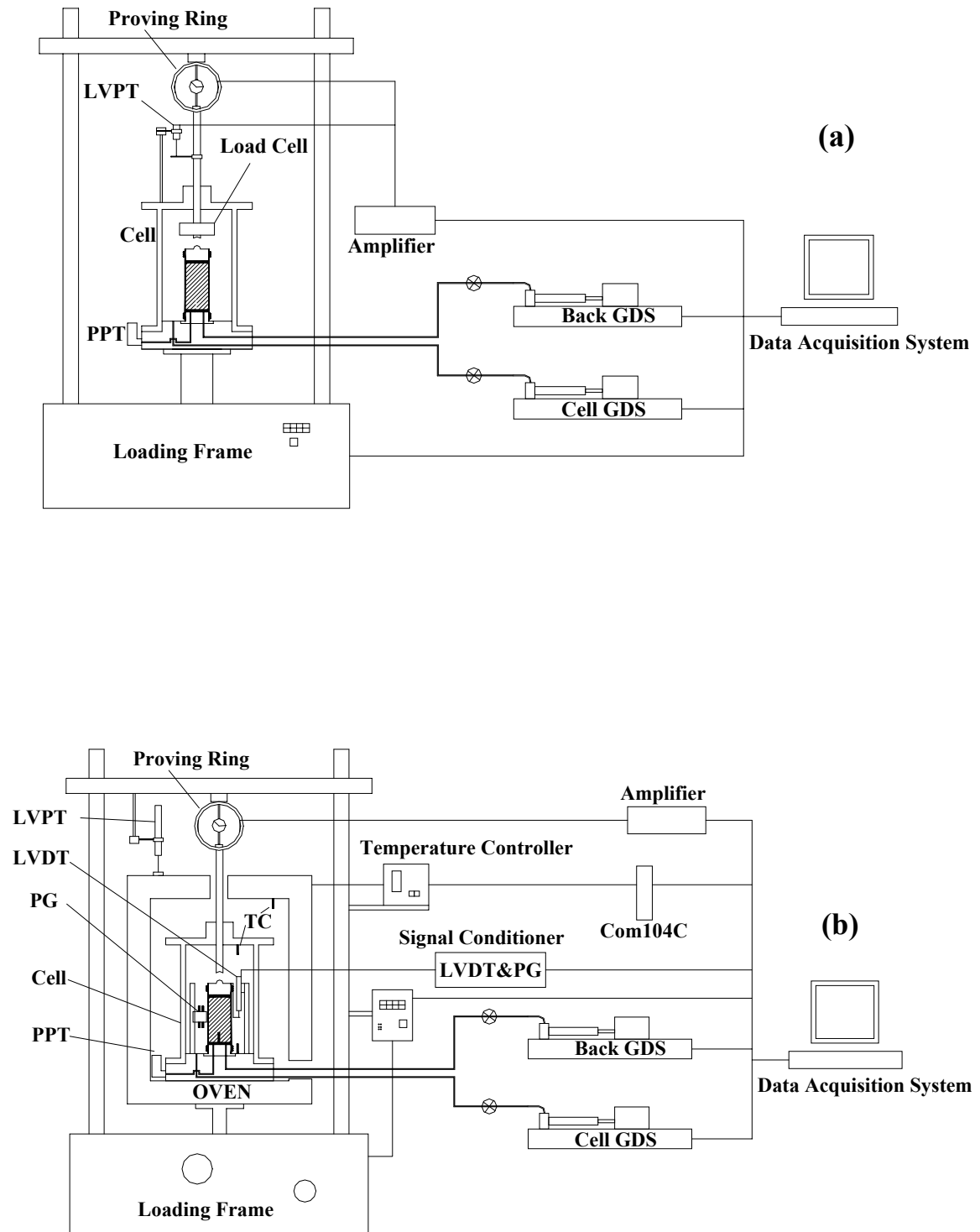


Figure 3.2 General layouts of a) conventional triaxial apparatus and b) fully automated high temperature triaxial apparatus (FHTTA)

Signal conditioners, amplifiers and analogue/digital computer boards interface the measuring and controlling devices to a personal computer used for data acquisition. Figure 3.3 shows the overall view of the FHTTA.

3.2.3 Description of equipment and calibration

The details of all the apparatus parts and their calibration procedures are given in the following sections.



Figure 3.3 Overview of equipment used for high temperature triaxial test

3.2.3.1 Load frame and load measurement

The axial compression is applied by a 50 kN-loading frame (Figure 3.3), which is driven by an electric motor through a geared transmission capable of moving the loading ram with different speeds from 0.0001 to 5.999 mm/min. The axial load is measured by an external strain gauged proving ring with a capacity of 4.5 kN. The proving ring is mounted under the crosshead beam on the top of the loading frame. Two strain gauges were mounted on opposite inner sides and a dial gauge in the centre of

proving ring was used to monitor the load. Any application of load to the proving ring generated an output voltage that was subsequently used for load measurement.

During the tests at elevated temperature, the proving ring was isolated from the oven by a 5 cm thick layer of glass wool, and a cooling fan was used to keep the ring's temperature constant at 22°C. Calibration of the proving ring was carried out only at ambient temperature because with this arrangement it had been found to be independent of the oven temperature (Chiu, 1996). The proving ring was calibrated for the range from zero to 2 kN, as the upper value was big enough to fail the sample at the highest cell pressure used in this study of 1200 kPa. The loading ram at all times was lubricated by silicon oil, and the frictional forces were found to be always under 30N. Figure 3.4 shows the variation of load with output voltage. It is clear that the relationship is linear and the equation of this line was used in the computer program for voltage conversion to load.

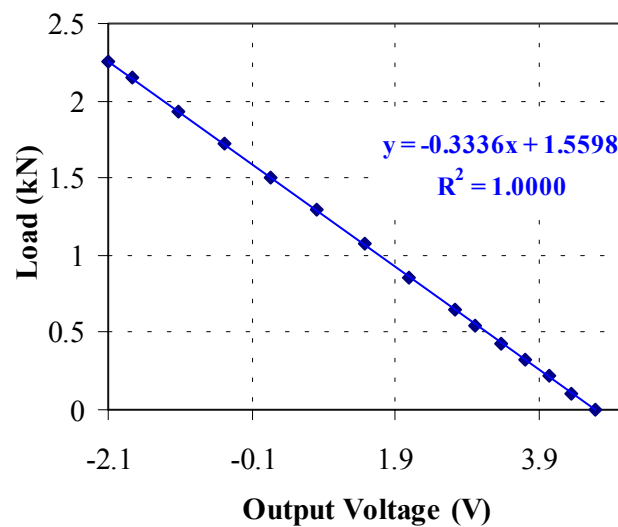


Figure 3.4 Variation of load with output voltage

Several attempts were made to source an internal load cell but the few companies who could provide a load cell at that time had difficulties in terms of calibration and waterproofing. A company called Sensotec made a waterproof high temperature load cell to our specifications, but it was delivered too late to be used in the test programme. The specification and calibration details have been written in appendix 3.A for future reference.

3.2.3.2 Triaxial chamber

Figure 3.5 schematically illustrates the sections of the triaxial cells used for permeability and triaxial compression tests. The permeability test compression chamber was a conventional Perspex triaxial cell that consists of a top plate and a base plate separated by a transparent cylinder.

Legend

- 1- Thermocouple, 2- Top cap, 3- Ceramic stand, 4- Viton O-ring, 5- Proximity Gauge
6- LVDT, 7- Butyl-rubber membrane, 8- Porous stone, 9- PPT

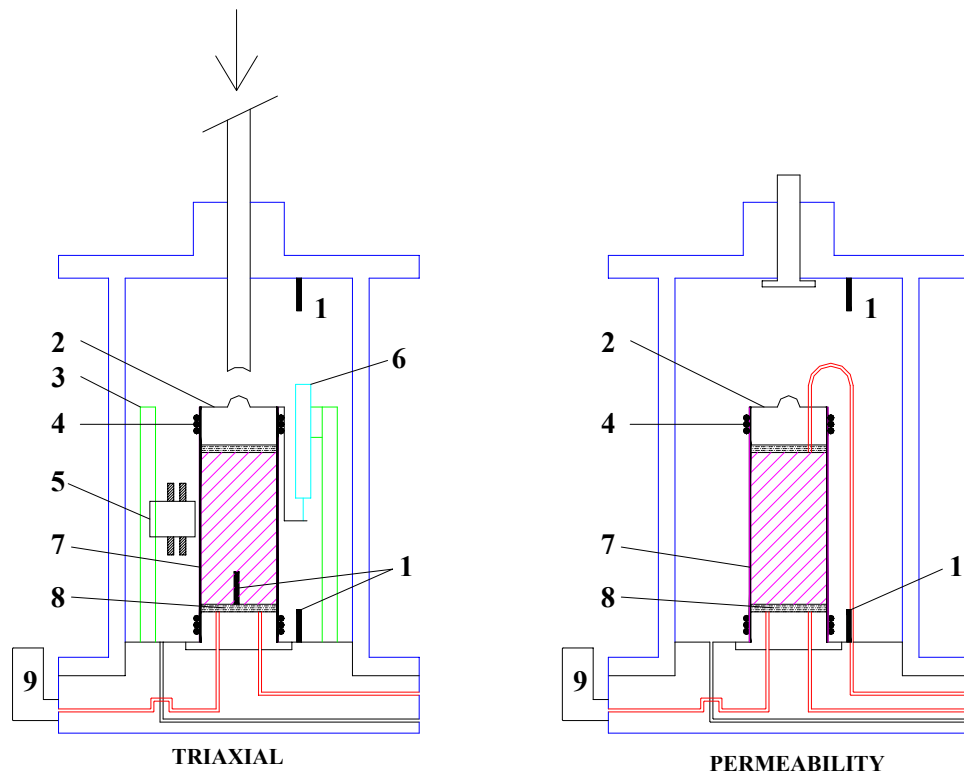


Figure 3.5 Sections of compression chambers used for triaxial and permeability tests.

The triaxial cell used in the FHTTA was manufactured from mild steel and had been plated by zinc (Chiu, 1996). It is capable of performing triaxial tests with maximum cell pressures of 4.5 MPa and temperatures of up to 200°C. The dimensions are: 150 mm internal diameter, 11 mm wall thickness, 250 mm cell height, 15 mm top plate thickness and 25 mm bottom plate thickness.

For the current research, the cell needed some minor modifications. Firstly, the zinc plating on the internal faces of the cell had been unsuccessful and corrosion of the steel caused problems with the sealing, as well as requiring cleaning between tests. In the

first attempt to eliminate corrosion, the internal wall was painted by a special epoxy paint but unfortunately, as is demonstrated in Figure 3.6, after testing at 100°C the paint started to bubble. The internal walls of the cell, and top and bottom plates were then covered by a special steel powder. This largely reduced rusting, but could not completely remove it. Secondly, Chiu (1996) showed that there was a temperature difference of about 10°C from top to the bottom of the triaxial cell at 100°C. He reduced this by using a 6.8 mm thick hard Muscovite insulating board underneath the cell, which limited the temperature difference to 2°C over the 100 mm height of the sample. However, the Muscovite could have led to under estimation of the axial deformation because of deformation in the insulating board and an alternative method of reducing the temperature gradient was desirable. The temperature gradient was caused by conduction through the base of the oven. To minimise this effect and allow the convection of hot air under the chamber a steel plate with a thickness of about 3 mm was cut into a partial spiders web (one small circular strip in the centre followed by radial strips) and was screwed to the base plate. This reduced the temperature difference to about 4°C from the top to the bottom of the triaxial cell, which implies a temperature difference of less than 2°C between the top and bottom of a 100 mm height sample. This temperature variation is not expected to significantly affect the results.



Figure 3.6 The failure of epoxy paint as cell's coating

3.2.3.3 Temperature controlled oven

The oven's profile is schematically shown in Figure 3.7. It consists of a 1000 Watt coiled heater, a fan in front of the heater, baffles to direct airflow, and a K-type

thermocouple connected to a temperature controller unit. The oven has been designed for temperatures up to 200°C. The fan helps the uniform circulation of hot air around the cell. The oven also has three portholes on the sides and ceiling to provide access for copper tubes supplying water to the cell and sample, wires connected to the instrumentation and loading ram.

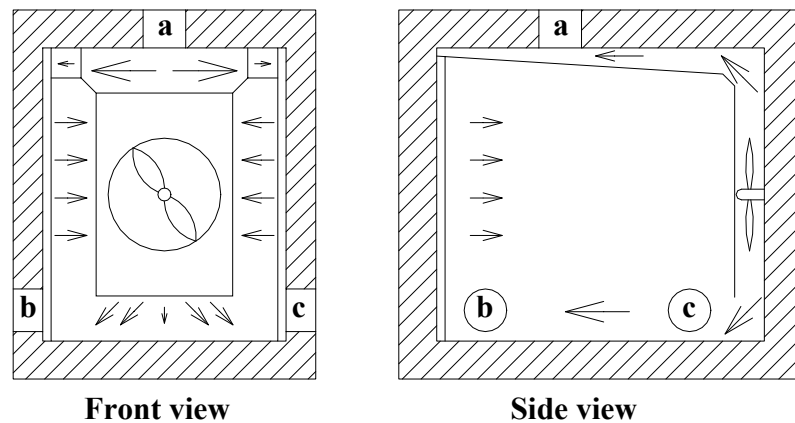


Figure 3.7 Cross sections of the temperature controlled oven (after Chiu, 1996)

The temperature in the oven was previously controlled by a REX-C10 controller, which only allowed manual adjustment of temperature. It was replaced with a more sophisticated REX-D400 controller to permit monitoring and control of the oven by the computer. An RKC COM104C was required as an interface between the oven and the computer to enable communication. The difference between the temperature measured in the oven and the temperature shown on the controller was always under 1°C. The measuring accuracy of the controller was $\pm 0.3\%$ of range span +1 digit. The detailed specifications of the controller can be found in appendix 3.A. During the tests, a Windows based computer program was in charge of any change in temperature. It should be mentioned that all the equipment outside the oven was in a laboratory with a constant temperature maintained at $22^\circ\text{C} \pm 1^\circ\text{C}$.

3.2.3.4 GDS digital controllers and drainage lines

Cell, and pore pressures and volume changes during permeability and triaxial tests were controlled and measured by GDS controllers with capacities of 2 MPa. Their detailed descriptions have been discussed by Menzies (1988). The tubing between the GDS

controllers and the cell was made of copper to ensure satisfactory performance at elevated temperature and pressure. This tubing has higher thermal conductivity than normal nylon high-pressure tubes, and this has ensured that the temperature of water entering the pressure controllers, determined by two thermocouples, was always within the range of $22^{\circ}\text{C} \pm 1^{\circ}\text{C}$. Two pieces of braided tube that had been used by Chiu (1996) were replaced by normal copper tubes because they were found to leak slightly at elevated temperature. This finding suggests that the previous test results reported by Chiu, (1996) at elevated temperature could have been slightly influenced by leakage. The pressure measurement resolution is 0.2 kPa and it can be controlled to 0.5 kPa but the accuracy of measurements has been reported to be within ± 4 kPa over a range from 0 to 2000 kPa (Chiu, 1996). The volume measurements according to the manufacturer have an accuracy of $\pm 0.25\%$ of the measured volume.

The calibration of volume changes in the pore water drainage system during heating and cooling was performed using a porous disc, two filter papers (50 mm diameter), a brass dummy sample and strip filter papers. All the drainage lines were filled with distilled de-aired water then a porous disc, two filter papers and the dummy sample were put in place and covered with an impermeable top cap. The dummy sample was then isolated by a butyl rubber membrane and sealed off with six Viton O-rings (3 on the bottom and 3 on the top). Then the cell was filled with distilled de-aired water and two heating-cooling cycles of $(22-100-22)^{\circ}\text{C}$ and $(22-50-75-22)^{\circ}\text{C}$ were followed under a cell pressure of 1000 kPa. A similar thermal cycle of $(22-50-75-100-22)^{\circ}\text{C}$ was repeated with a closed drainage tap to indicate the volume change in the tubing between the tap in the oven (used to isolate the sample in undrained loading) and the GDS. The results are shown in Figures 3.8a, 3.8b and 3.9. Figure 3.8a demonstrates the variation of temperature in the centre of sample with time for the first part of the calibration test and indicates that equilibrium has been achieved at each step before heating to the next higher temperature. It is clear from Figures 3.8b and 3.9 that the total volume changes during heating and cooling are equal. In the previous HTTA (Chiu, 1996) a similar test had indicated a small volume loss. It was found that this was caused by leakage from the flexible braided tube used by Chiu to facilitate positioning of the cell in the oven. This zero volume loss with the new tubing shows that the leakage in the braided tubes has been eliminated. During undrained heating the tap (in the oven) between the GDS and the cell is always closed so the difference between the total change and the change

with the closed tap (Figure 3.8b) indicates the amount of water flowing into the clay sample. During heating from 22°C to 100°C (first thermal cycle), the total and closed tap volume changes of 860 mm³ and 265 mm³ were measured respectively. Therefore during undrained heating to 100°C the amount of 595 mm³ (a volume strain of about 0.3%) will flow to the clay sample, and during drained heating the measured volume of drained water will be overestimated by 860 mm³ (a volume strain of about 0.4%). A similar approach was used for calculations of volume corrections during heating to 50°C and 75°C. The hysteresis shown in the volume change with temperature graph (Figure 3.9) is believed to be the result of different rates of heating and cooling. The rate of heating was set to 0.1°C/min while the rate of cooling was slower and controlled by the rate of convection from the oven to the room. The observed hysteresis can also be related to the fact that tubes in the oven heat up quickly, whereas some time is required for the triaxial cell to be uniformly heated. It is clear from Figure 3.9 that the cooling curves coincide with each other and are close to the equilibrium points at 50°C, 75°C and 100°C. The red line is suggested to be the equilibrium curve, and has been used for correction of volume change at other temperatures.

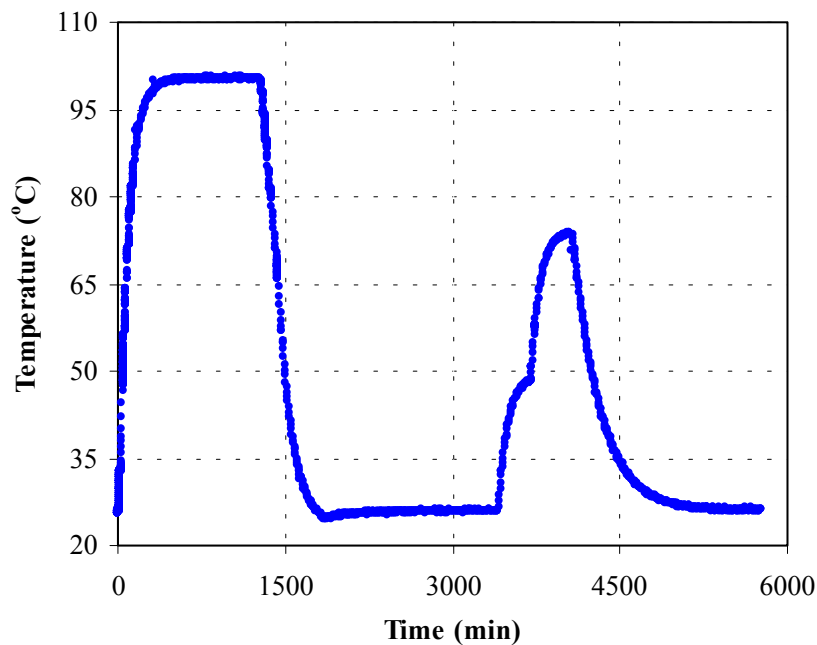


Figure 3.8a Changes in the temperature of sample with time during calibration

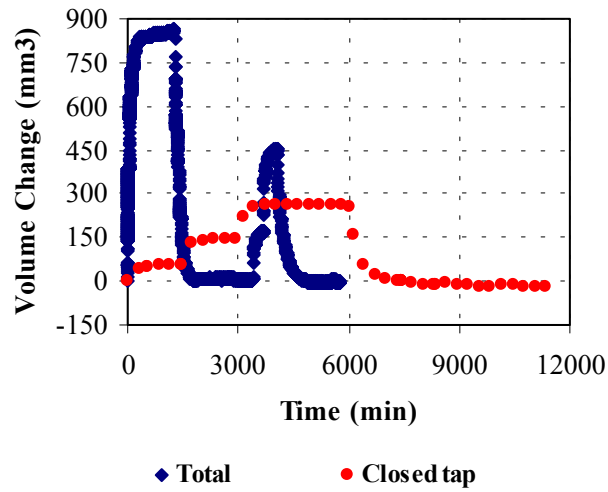


Figure 3.8 Changes in the volume of water with time during calibration

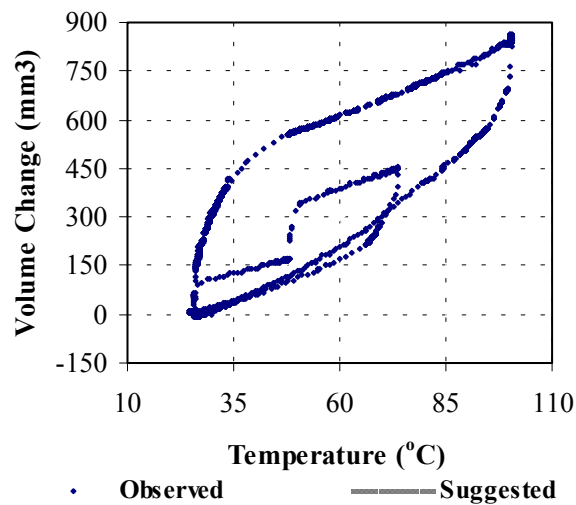


Figure 3.9 Changes in the total volume of water with temperature during calibration

3.2.3.5 Membrane, Porous stones and Top cap

As shown in Figure 3.5, the bottom of the sample is connected to the base of the triaxial apparatus through a filter paper and porous stone. In the previous design of the HTTA (Chiu, 1996) the brass top cap was connected to a pore water drainage line in the base of triaxial cell using a spiral copper tube. In the new system (FHTTA), this tube has been removed in order to avoid the problems associated with its stiffness (especially for soft clay i.e. sample disturbance, tilting of top cap etc) and to minimize the volume of water in the drainage lines. The top of the sample is covered by a filter paper and the new

impermeable ceramic top cap. The top cap has been made of ALSINT 99.7 an alumina ceramic with a linear coefficient thermal expansion of $7 \times 10^{-6}/^{\circ}\text{C}$ within the temperature range of 20°C to 300°C . Two folded strips of steel were screwed to the top cap in order to accommodate and measure the top cap displacements by internal LVDTs. The use of ceramic strips was considered but due to the limitations in the size and shape of the folded strips and casting difficulties only metal strips could be accommodated.

It was expected that with the removal of the top drainage line the time for consolidation would dramatically increase. In order to reduce the duration of consolidation and accelerate the equalization of pore pressure during shearing, strips of filter paper were used to enable radial drainage. Leroueil et al (1988) reported that the permeability of filter strips decreased with time and their drainage capacity decreased with increasing confining effective stress. They also showed that by using radial drainage the time of 100% consolidation for clay sample has been reduced by a factor much less than 5 to 10 (calculated from Bishop and Henkel's approach, 1962) and no corrections of shear strength were needed for spiral strips. The efficiency of filter strips was investigated during isotropic consolidation tests on Kaolin C1C and the results confirmed Leroueil et al's findings. These results are further discussed in chapter 4.

Butyl rubber membranes were used to isolate specimens from the cell water. Six Viton O-rings were employed to clamp the membrane to the top cap and base of the triaxial cell. The membranes had been previously tested and found to be impermeable at temperatures up to 110°C by Chiu (1996). Butyl rubber is soft, stretchy and flexible but less so than conventional latex membranes, and its average thickness is about 0.7 mm. In order to avoid any errors in data interpretation the forces applied by the membrane must be taken into account. Therefore, the membrane Young's modulus, E_M , was determined using a 25-mm circumferential strip of membrane hung between two thin steel rods and loaded with known masses (Bishop and Henkel, 1962). Figure 3.10 illustrates the membrane deformation with application of load. The value of 3177 kPa for E_M , corresponding to 15% extension, has been used during correction of the results in chapter 4.

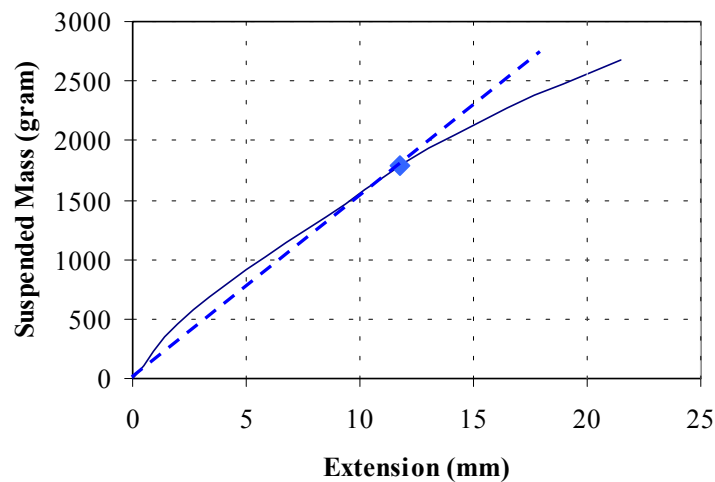


Figure 3.10 Changes in the length of membrane strip with load

3.2.3.6 Ceramic stand

The ceramic stand used in the previous study (Chiu 1996) was completely redesigned and was built from the same material as the top cap, ALSINT 99.7 alumina ceramic. The new stand was designed in order to accommodate the LVDTs for measurement of axial deformation and proximity gauges for measurement of radial deformation. The alumina ceramic stand has a linear coefficient thermal expansion of $7 \times 10^{-6}/^{\circ}\text{C}$ within the temperature range of 20°C to 300°C . This material was selected because with a relatively low coefficient of thermal expansion, the amount of error introduced in the measured displacements would be minimised. It was possible to select a ceramic material with an almost zero coefficient of thermal expansion, but this type of material was weak and brittle and would not have been suitable for the ceramic stand. The ceramic used was a compromise that was selected considering cost, availability and ease of manufacturing. Initially a prototype stand was designed and made from Perspex for use in room temperature tests and in order to check the design and to prepare a mould for the casting of the ceramic stand. Figure 3.11 shows a picture of the Perspex stand. It consists of two Perspex clamps to hold the LVDTs and two holes on each side for installation of proximity gauges. After successful mounting of the internal instrumentation on the Perspex stand, a ceramic stand was built with a few minor changes to the prototype. Figure 3.12 shows the ceramic stand that was employed in triaxial tests at elevated temperature. The clamps for the LVDTs were made of stainless steel because of difficulty in casting these accurately.



Figure 3.11 Picture of Perspex stand



Figure 3.12 Picture of ceramic stand

3.2.3.7 Displacement measurement

The vertical displacement of specimens was determined externally using a linear variable potentiometer transducer (LVPT). The operational range of the LVPT is around 114 mm and it has a resolution of 0.07 mm. The output voltage is dependent on input voltage and the position of the moving wiper. An input voltage of 5 volts DC was

employed. In order to calibrate the LVPT a set of steel slip gauges were used to provide different displacements. The changes in output voltage with displacement are plotted in Figure 3.13.

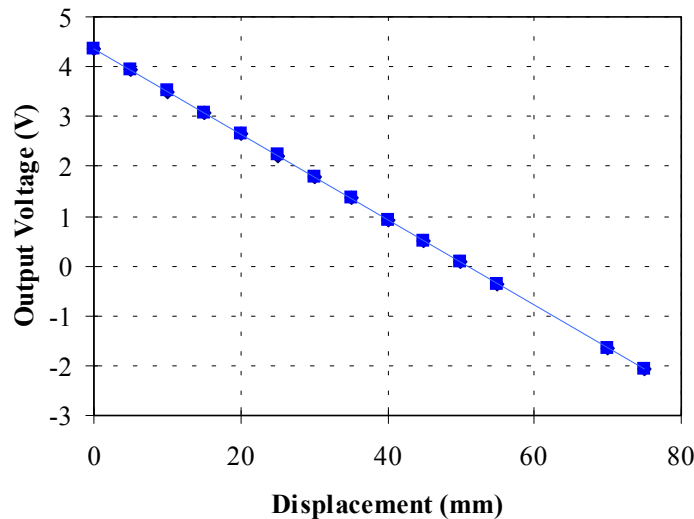


Figure 3.13 Result from calibration of external LVPT

The equation for the trend line passing through all data points was used for calculation of displacement. The LVPT is located outside the oven and its temperature has been kept constant at 22°C using the proving ring's cooling fan. Therefore, high temperature calibration was not necessary.

One of the biggest challenges in this research was the use of internal measuring devices for direct small strain measurement. As previously discussed in the literature review, internal displacement devices have rarely been used in high temperature triaxial testing of soil because of sealing and calibration difficulties. In the current study, two LVDTs and two PGs (proximity gauges) were implemented for small strain measurement. Figure 3.12 clearly shows the location of these devices. The LVDTs were manufactured by RDP Electronics Ltd (TypeD5/200AW/377) and have a nominal working range of 10 mm with a linearity of 0.3% at 20°C. The wiring information and manufacturer calibration data sheets can be found in appendix 3.A. The time for manufacturing and delivery to Australia was given as six months and they had to be replaced a couple of times because of a sensors failure at 120°C. The associated delays and recalibration have unfortunately limited the test program. The working temperature range of these

LVDTs has been reported to be between 20°C and 200°C. The lateral displacements of the samples were measured by two proximity transducers, which were made by Sangamo Ltd (type DT 18M). They have a working range of 5 mm at 22°C. Their specifications are also reported in appendix 3.A. All LVDTs and PGs were excited with 3V rms power using OD5 transducer conditioners (made by Schlumberger Ltd) at a frequency of 5kHz. For the purpose of calibration at room temperature two calibration fixtures shown schematically in Figures 3.14A and 3.14B were employed.

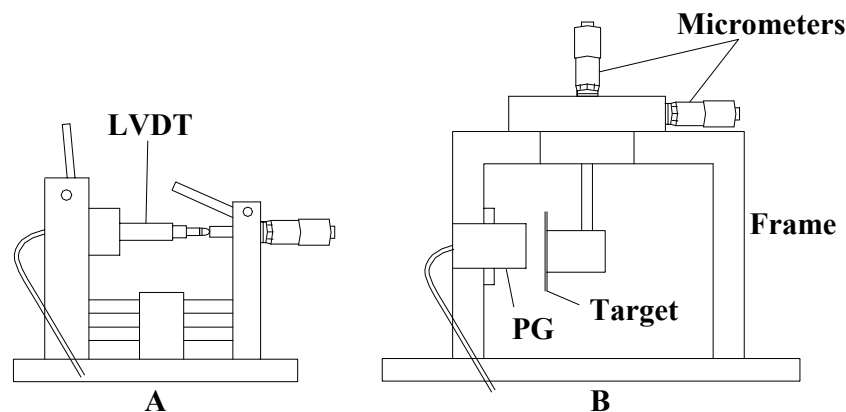


Figure 3.14 Schematic drawings of calibration setup for LVDT and PG

The fixture in Figure 3.14A was used for LVDT calibration and was implemented with a micrometer measuring the displacement horizontally. In Figure 3.14B, the frame is Perspex and is provided with two micrometers perpendicular to each other. They are both connected to a non-rotating non-magnetic shaft. The 20x40 mm target (identical to that used in the tests) is located at the end of this shaft. In addition to horizontal and vertical movement, the shaft and target were able to rotate around the shaft axis. The angle of rotation could be measured on the top of the fixture. The target induces an Eddy current in the PG coil, which in turn can be used for measurement of displacement. The target was arranged to rotate and move vertically in order to check the effects of rotation and vertical movements on the measured values during the real tests. Both fixtures were designed and made in the department of Civil Engineering at the University of Sydney. The micrometers could produce direct displacement of the LVDT core and displacement of the proximity gauge target. The output signals were

amplified to provide a $\pm 5\text{V}$ full-scale output. The output of one of the LVDTs is plotted in Figure 3.15.

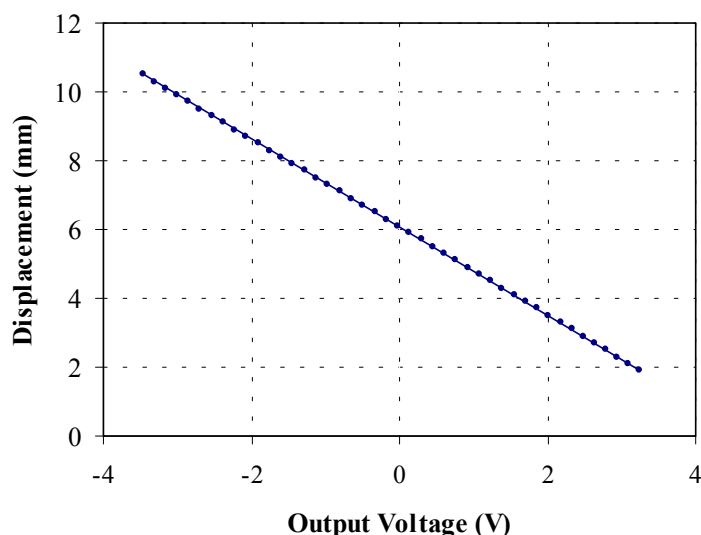


Figure 3.15 LVDT calibration at ambient temperature

The slope of the trend line in the graph was used in the program to convert voltage readings to displacement measurement during the tests at room temperature. For calibration at higher temperatures, a 100 mm tall ceramic hollow cylinder dummy sample with external diameter of 50 mm and wall thickness of 5 mm was used. During calibration, a porous disk, two circular 50 mm diameter filter papers (Whatman No.54) together with the dummy sample were mounted in the triaxial cell as shown in Figure 3.12. As has been mentioned earlier, the ceramic material has a relatively low coefficient of thermal expansion compared to the soil specimens. The calibration was performed in 8 steps. For each step the position of the LVDT was changed by between 1 mm to 1.5 mm from the previous step. In every step, the temperature was raised at $0.1^\circ\text{C}/\text{min}$ from 22°C to 50°C , 75°C and 100°C and held constant for about 12 hours at each value, then it was cooled down to 22°C all under constant cell pressure of 900kPa and back pressure of 500kPa. The recorded voltages are plotted against displacement in Figure 3.16. The amount of thermal expansion of the ceramic dummy sample has been determined and considered in the calculations of displacement at each stage. After calibration, the thermal expansion of known materials has been determined and results are presented later.

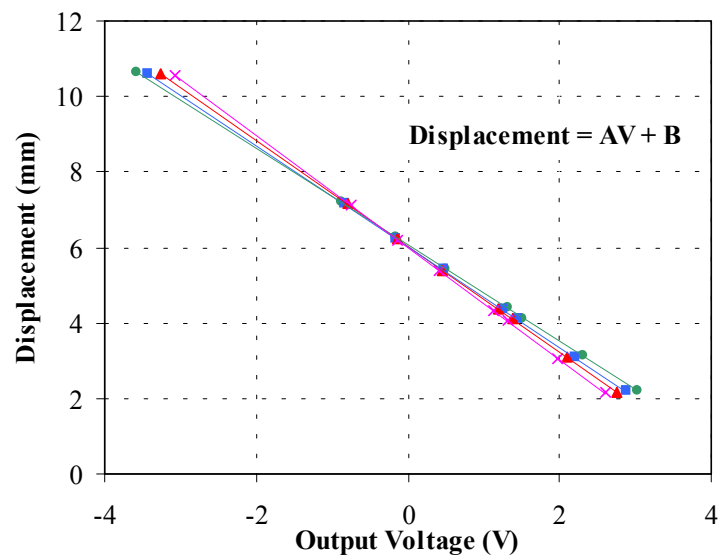


Figure 3.16 Results from calibration of LVDT's at elevated temperature

The green, blue, red and magenta colours represent temperatures of 22°C, 50°C, 75°C and 100°C respectively. It can be noticed from the graph that although the relationship between displacement and voltage is linear at all temperatures, the slope of the trend lines increases with temperature. The changes in the values of A and B (slope and intercept) of all four lines are drawn versus temperature in Figure 3.17.

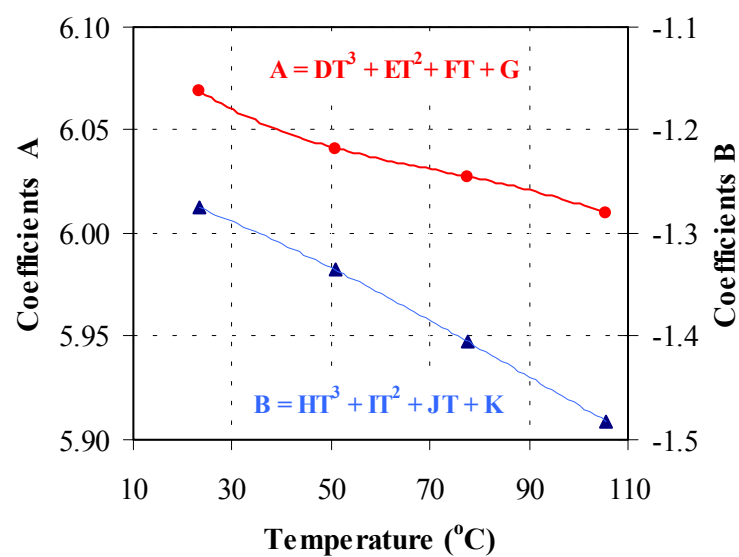


Figure 3.17 Changes in the coefficients of A and B with temperature

To reach an accuracy of better than ± 10 micron a third degree (Lagrange) polynomial was fitted to both A and B data points. The factors of both equations (D,E,F,G,H,I,J,K) were placed in the computer program for conversion of voltage to displacement at any temperature.

The calibration of the proximity gauges at room temperature was carried out using the setup shown in Figure 3.14B. The target was made of galvanized steel with the dimensions of 20x40x1 mm. At the beginning of calibration, the target was located parallel to the face of proximity transducer with a separation of very close to zero. The target was slowly moved away from the PG by the horizontal micrometer. The output voltage after amplification by the OD5 signal conditioner was recorded. The results are illustrated in Figure 3.18.

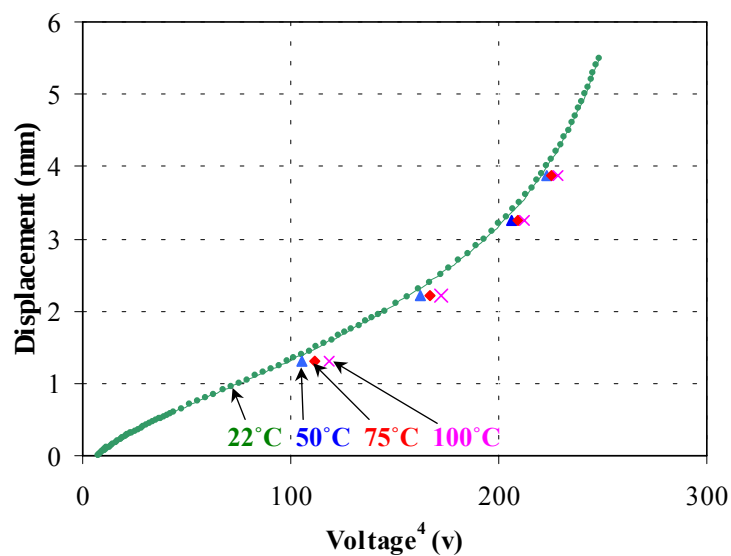


Figure 3.18 Changes in output voltage of proximity gauges as the target separation increases

The x-axis is the fourth power of voltage because of the limitation in MS Excel to fit higher order polynomials. A sixth order (Lagrange) polynomial was fitted to the room temperature (RT) data using the least squares method. The equation of this curve was used for calculations of radial displacement at room temperature. It has been reported by Hird and Yung (1989) and Scholey et al (1995) that misalignment and bad positioning of the target could introduce errors in the measurements of displacement. These errors would be more significant for soft soils during saturation and consolidation stages. However, it was found that the vertical movement of target during calibration did not

affect the PG's output as long as the top of the target extended above the top of the face of the PG (and similarly at the bottom). During tests on soft clay movements due to non-uniform deformation of the sample are expected that could cause some rotation of the targets. However, a rotation of about 5 degree was found to have insignificant effects on the output voltage.

High temperature (HT) calibration of the PGs was carried out simultaneously with the LVDTs. Targets similar to the room temperature targets were stuck on the membrane at opposite sides of the dummy sample. Different separations at each step were set by adjusting the PG's clamping nuts (as shown in Figure 3.11, there are two installation nuts on the threaded outer case of each proximity gauge). The changes in output are shown on Figure 3.18 next to the room temperature data. The green, blue, red and magenta colours represent temperatures of 22°C, 50°C, 75°C and 100°C respectively. It can be seen that effects of temperature are more significant at lower separation. It was considered that the expansion of the ceramic stand and dummy sample were similar and compensating for each other so, all the changes should have come from variation in the transducer's output. Therefore, to allow for the temperature effects the HT voltage has been corrected to the voltage at 22 °C to evaluate the separation between PG and target. To then determine the correct displacement of the soil the thermal expansion of stand ($R_{\text{stand}}\alpha\Delta T$) should be added to the displacement predicted at room temperature. Figure 3.19 shows that the variation of output voltage with temperature for a constant separation is linear so, the best trend lines were drawn through the data points.

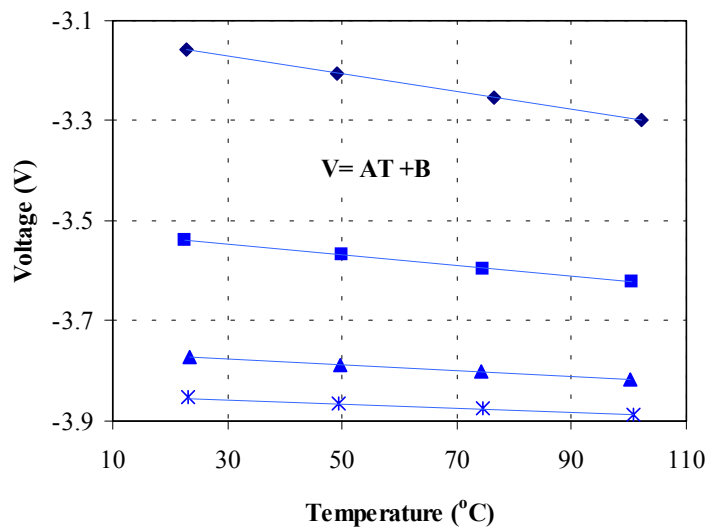


Figure 3.19 Variation of PG's output voltage with temperature

The values A and B were extracted from Figure 3.19 and plotted in Figures 3.20A and 3.20B against initial output voltage at ambient temperature. The linear variations shown in these Figures enable the values of A and B to be easily calculated as functions of the initial RT voltage. Consequently all voltages recorded at higher temperature during the test can be transformed to RT voltage using A, B and temperature. Then the corrected voltage can be put in the equation of the room temperature curve in Figure 3.18 to calculate displacement.

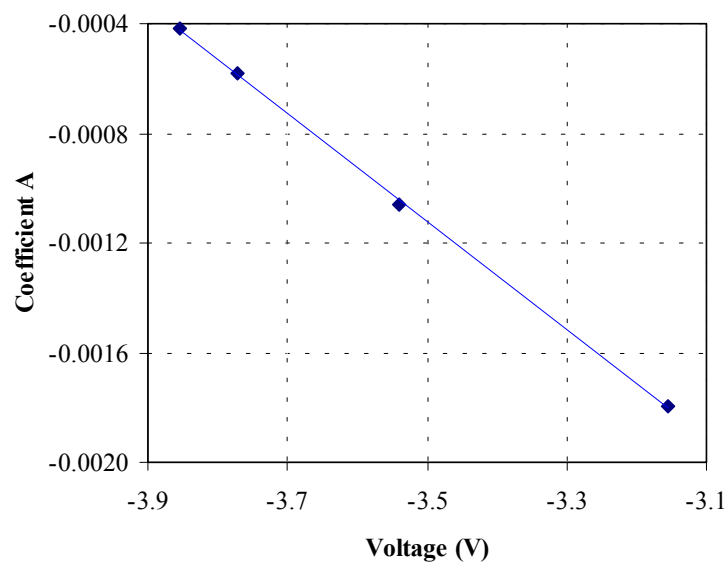


Figure 3.20A Changes in factor A with variation of initial output voltage

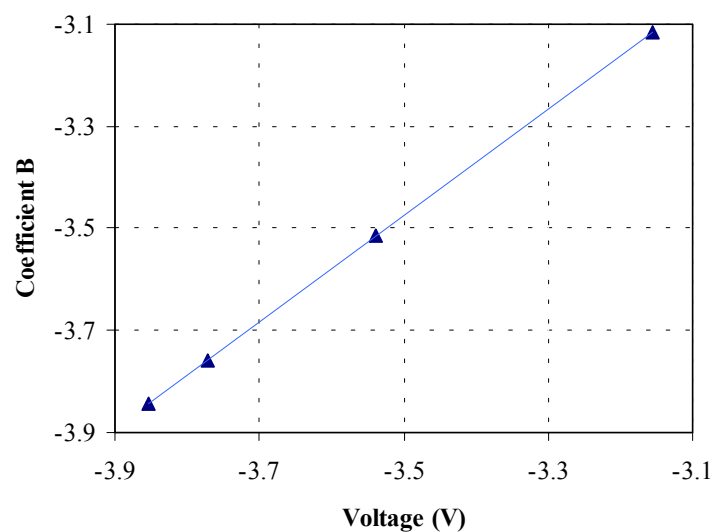


Figure 3.20B Changes in factor B with variation of initial output voltage

The calibration of the LVDTs was checked using three cylindrical dummy samples (50 mm x 100 mm) made of Brass, Aluminum and Lead with linear coefficients of thermal expansion (α) of 18.7×10^{-6} , 23.5×10^{-6} and $29.1 \times 10^{-6}/^{\circ}\text{C}$ respectively (Perry's Chemical Engineer's handbook, 1997). The LVDTs were set in place and temperature was raised in three steps to 100°C . The axial strains (%) are plotted versus changes in temperature in Figure 3.21. The slopes of lines present the reported values of α by Perry (1997). It can be seen that the measured values are very close to the reported values. The lead dummy sample was moulded in the workshop from small pieces of lead so in this case the slightly higher α could be related to inconsistency in moulding or material. Also it is clear that the accuracy of measurements reduces at higher temperatures. However, the results confirm that the coefficient of thermal expansion of soil samples can be measured with reasonable accuracy. The accuracy of the calibrations is further discussed later in this chapter. It was not possible to check the reliability of the PGs calibration because their responses were significantly affected by the metal dummy samples.

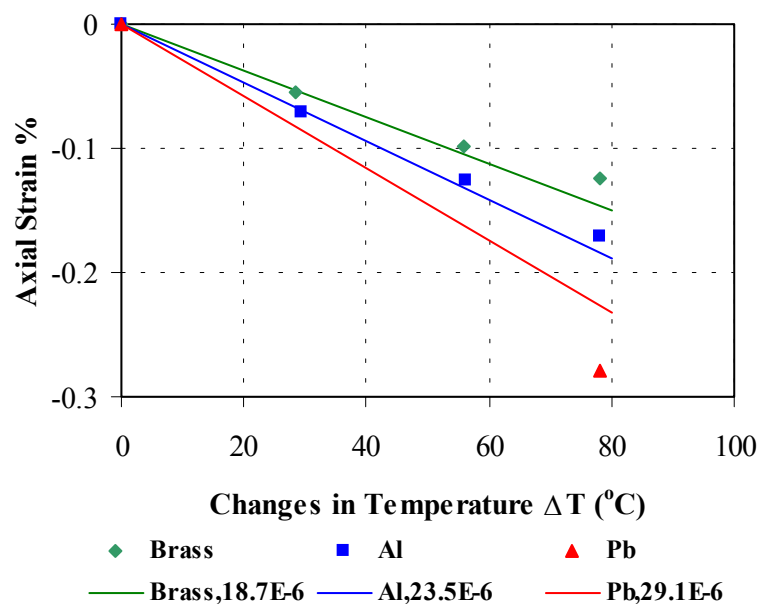


Figure 3.21 Measured and reported (Perry, 1997) values of α for 3 metals

One of the proximity transducers stopped working during the first triaxial test at elevated temperature. Replacement was not possible because the manufacturer had stopped the production of this type of transducer. A similar non-contact position

measuring device (type K μ DA, 12u) was bought from Kaman instrumentation. It was calibrated at room temperature but sealing the sensor itself in the cell was unsuccessful because of soft connection leads. The specifications of this sensor together with its signal conditioner are reported in appendix 3.A.

3.2.3.8 Pore water pressure measuring devices and their calibration

The pore water pressure during permeability and triaxial testing was measured by a Kyowa PIT-50B pore pressure transducer (PPT) that was mounted on the cell base inside the oven. It has a working range of zero to 5 MPa at temperatures between -196°C and 220°C. The output voltage was amplified to give -3V to +5V output for a pressure change from 0 to 3 MPa. For calibration of the PPT the cell was filled with water, then the pressure of the cell was incrementally increased by a GDS pressure controller in steps of 100 kPa to a maximum pressure of 3000 kPa and simultaneously output voltages were recorded. The results are shown in Figure 3.22. The calibration confirms a linear relationship between pore pressure and output voltage. The calibration of the PPT at elevated temperature showed that a temperature increase from 22°C to 100°C did not affect the slope of calibration line but shifted the measured pressure to a value of 20 kPa less than before. This variation was found to be linear with changes in temperature. This should be considered during any course of undrained heating. The pressure readings of the PPT were found to be within ± 1 kPa difference from those measured by the GDS in the range from 0 to 3000 kPa.

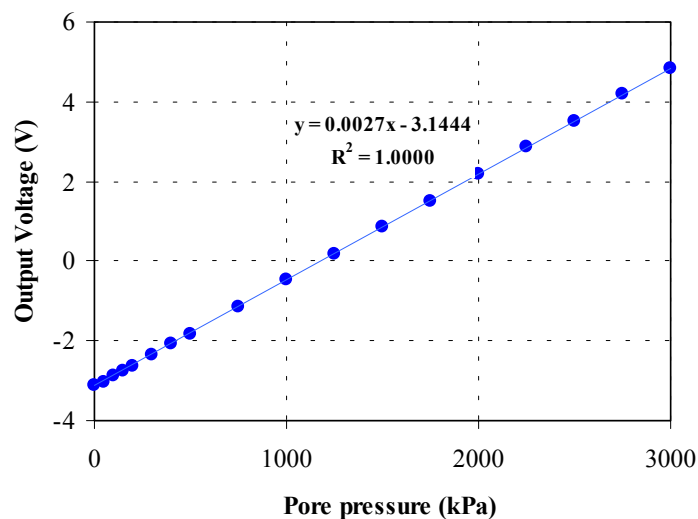


Figure 3.22 Result from calibration of pore pressure transducer

The difference between the pore pressure on the top and bottom of sample during permeability tests was measured using a differential pressure transducer (type P2144) manufactured by Lucas Schaevitz Company. It has a working range of 240 kPa differential pressure and a maximum pressure of 1.2 MPa at each side. The calibration was carried out only at ambient temperature because the DPT (differential pressure transducer) was mounted outside the oven between top and base GDS pressure controllers. During calibration, a pressure difference of -100 to 125 kPa was applied by GDS controllers and the output voltage was amplified and recorded. Figure 3.23 illustrates the voltage variation with changes in differential pressure.

The detailed specification of both DPPT and PPT are reported in appendix 3.A.

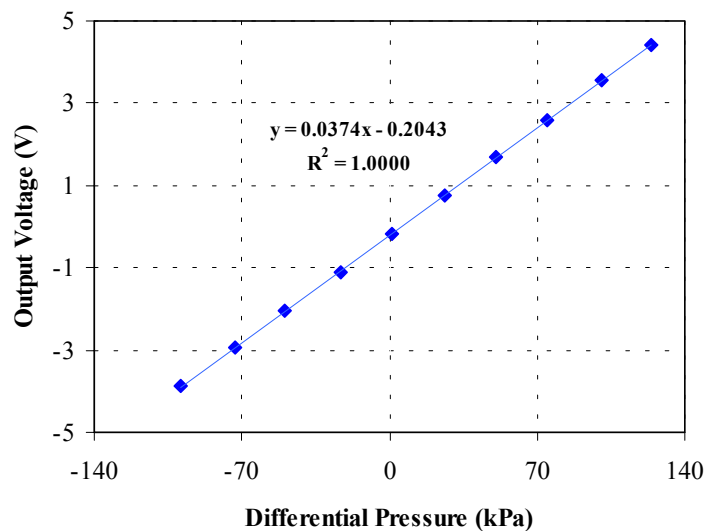


Figure 3.23 Calibration results of differential pressure transducer (DPT)

3.2.3.9 Thermocouples

Temperature measurement was carried out during permeability and triaxial test using K type thermocouples (TC) with grounded junctions. Type K thermocouples are constructed of Chromel/Alumel and their working range is from -200°C to 1250°C . The error limit is 2.2°C or 0.75% for temperatures above 0°C . In the triaxial and permeability tests 5 and 3 thermocouples were used respectively. The locations of the TCs have been shown in Figures 3.1 and 3.2. The calibration information provided by the manufacturer was used to transform output voltage to temperature. In order to check the calibration all thermocouples were mounted on a non-conductive electrical plate and were placed in the oven. Then temperature was increased to 110°C in three steps and the

temperatures measured by the TCs were compared with the readings of a mercury thermometer with an accuracy of 0.1°C , and with the readings of a precise millivolt potentiometer. The results showed that differences in the measurements were within $\pm 1^{\circ}\text{C}$.

3.2.3.10 Data acquisition system

The Data acquisition system consists of amplifiers, an RKC COM104C interface, a PC73 temperature A/D converter board, a CIO-DAS 1600 A/D converter board, GPIB card, a Pentium personal computer and 2 computer programs. The output voltage of the electronic measuring transducers after amplification goes to a distribution board and then to the DAS-1600 16 bit bipolar board to be converted to digital form. A Quick Basic (QB) program based on an earlier program (CGR Sydney University, 1991) was developed to monitor and control the following devices:

- Temperature controller through COM104c interface
- Loading frame through digital output of DAS-1600
- All 7 electronic measuring transducers through amplifier and Das-1600 board
- GDS pressure controllers through GPIB board
- Thermocouples through PC73 board.

In the program, the received output voltages of all the transducers are converted to pressure, load, displacement or temperature using the calibration curves and factors discussed previously in this chapter. All the interface boards were calibrated according to manufacturer instructions and plugged into ISA Slots and were set with different base addresses. The PC73 board is a 12-bit analog to digital converter that allows for eight differential inputs. It was used for a maximum of five thermocouples and was accessed within the program by Quick Basic routines provided by the manufacturer. The GDSs are controlled via a GPIB card (standard IEEE488 interface) from the program. CIO-DAS1600/16 is a 16-bit analog to digital converter and it can be set to either 8 differential or 16 single ended input channels. The oven's temperature controller is connected to the computer serial port via the RKC COM104C interface. The windows based program "WINSOI" provided by the manufacturer allows full access to the temperature controller. The developed QB program is quite user friendly and is capable

of continuous data recording and monitoring by its control algorithm. In addition to the above system, PCANYWHERE software was used to remotely monitor and control the progress of the experiments.

The complete specification of all the boards and interfaces can be found in appendix 3.B.

3.2.4 Error Assessment

Error evaluation has been emphasized by many researchers as an important aspect of all experimental procedures. There are three basic types of error (e.g. Germaine and Ladd, 1988) in any experimental work: precision, which is used to express the scatter around a mean value and involves only random errors; accuracy, which is the deviation of a measured value from the actual value which may result from either random or systematic errors; and resolution which is the smallest detectable measurement unit of a device. Reading errors and condition changes are the main sources of random error while systematic errors may be produced by the lack of a proper method of measurement i.e. an incorrect calibration method (Jones 1977). All transducers were used within the working ranges specified in the various manufacturers data sheets and their calibrations were regularly checked. During calibration of all electronic transducers, each reading was taken twice once when moving to the upper limit and once to the lower limit. The accuracy of transducers was always checked by comparison between the measured and true value. The accuracy of the LVPT was determined to be ± 0.07 mm plus ± 0.2 μ m resolution of steel slip gauges. The PPT and DPT were found to be within ± 4 kPa accuracy. Their response was determined to be quite repeatable and linear with changes in pressure. The resolution of the micrometer that was used to measure the displacement of the PGs and LVDTs was 0.01 mm and, as was mentioned earlier, the calibration was carried out by fitting the best trend line or Lagrange polynomial to data points using the least squares method. The accuracy of measurements made with the PGs may be assessed by referring to Figures 3.24A and 3.24B. It can be seen that a systematic error of ± 15 μ m for separation of target up to 5 mm from PG plus an error of ± 5 μ m for temperature elevation to 100°C are expected in the measurement of radial displacement. It should be noted that a use of higher degree polynomial during calibration could result in a lower deviation from actual values (Figure 3.24A) but as many other factors influence the response of the PGs it was

decided to not proceed with the complications associated with the use of a higher degree polynomial. The maximum total uncertainty might be $\pm 30 \mu\text{m}$ but the maximum probable error is $\pm 18.7 \mu\text{m}$ determined from adding individual errors in quadrature (square root of $10^2 + 5^2 + 15^2$). As it was mentioned earlier, the actual uncertainty may be higher as a result of target misalignment. Similarly, Figures 3.25A and 3.25B have been used to assess the accuracy of measurements for the LVDT's.

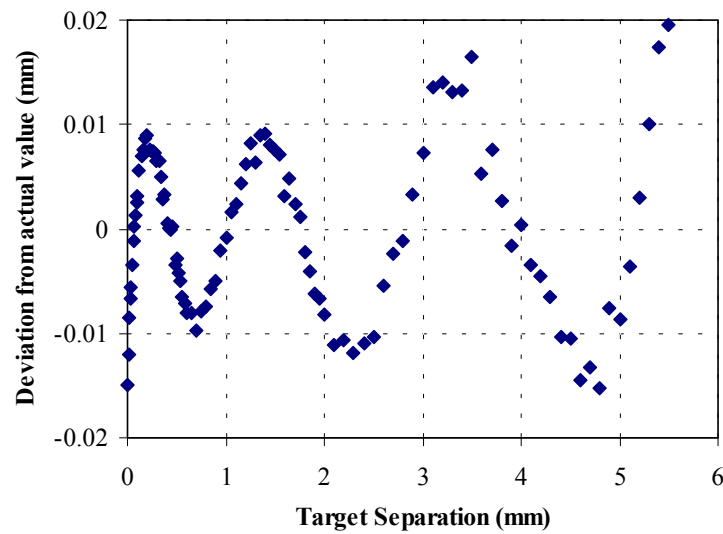
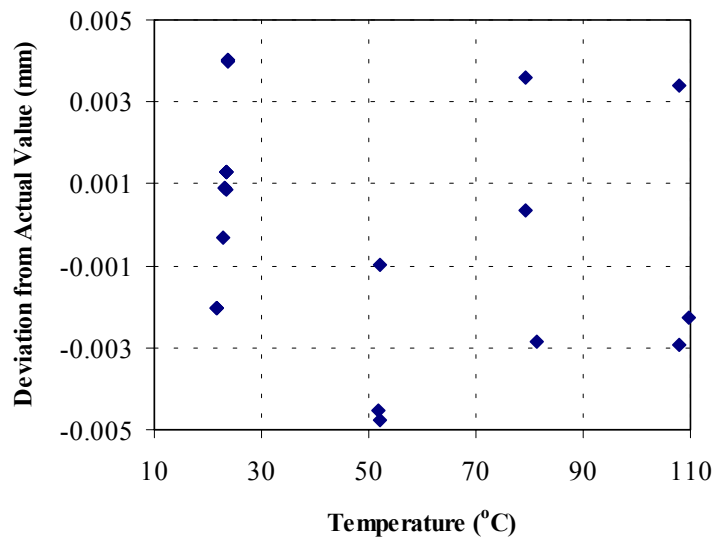


Figure 3.24A Variation of accuracy as the gap between the PG and target changes



3.24B Variation of measured error in the PG with changes in temperature

The maximum probable uncertainty would not exceed a total of $\pm 23 \mu\text{m}$ which consists of a $\pm 15 \mu\text{m}$ error of calibration at room temperature (Figure 3.25A) for displacements in the range of 0.7-10.5 mm, a $\pm 15 \mu\text{m}$ error due to temperature rise to 100°C (Figure 3.25B) and $\pm 10 \mu\text{m}$ due to the resolution of micrometer. Therefore, the maximum likely uncertainty in axial displacement is not expected to be bigger than $\pm 23 \mu\text{m}$. The axial load and temperature were measured with an accuracy of $\pm 2 \text{ N}$ and $\pm 1^\circ\text{C}$ respectively.

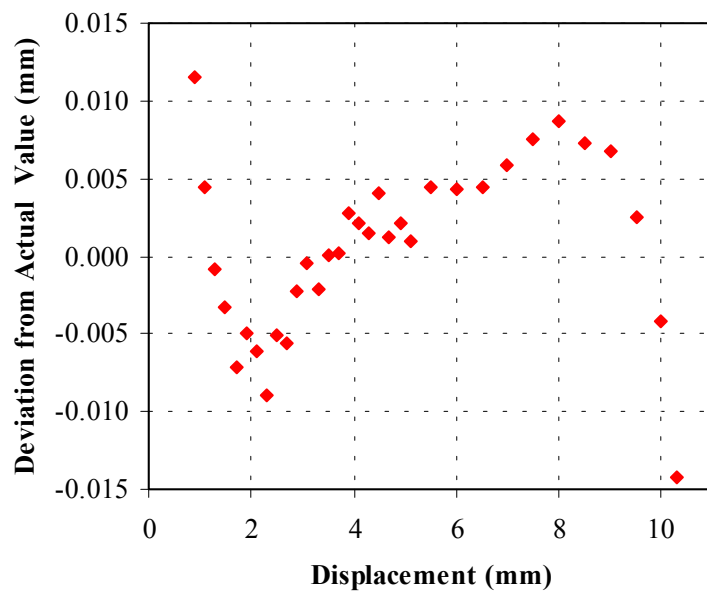
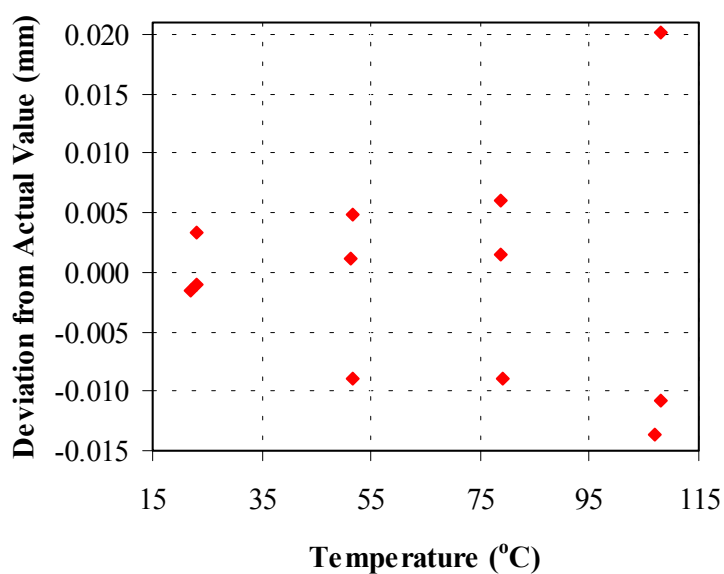


Figure 3.25A Variation of accuracy with displacement in the LVDTs



3.25B Variation of measured error in the LVDTs with changes in temperature

3.2.5 Suggestions for further improvement to the FHTTA

Although the current system is capable of running at elevated temperature and producing reliable data further developments are still necessary to minimize the errors and simplify the operation. They are recommended as follows:

- Replacement of the proximity gauges by alternative and more reliable displacement measuring devices such as LVDT's or fibre optic gauges. The proximity gauges have a limited working range and their accuracy is affected by misalignment of the targets due to the large deformation of soft soils during consolidation.
- Replacement of thermocouples by thermistors. This would improve the accuracy and sensitivity of temperature measurement.
- The current triaxial cell needs to be redesigned and rebuilt from stainless steel or possibly Pyrex in its cylindrical part in order to: firstly, provide room for an internal load cell and additional internal instruments such as fibre optic displacement transducers; secondly, eliminate the remaining amount of corrosion in the cell body especially in the base; thirdly, allow the proper air circulation under the cell's base; and finally, permit observation of samples during experiments in order to stop the test and save time when the sample is damaged, misaligned or has any other problem which can be visually noticed.

3.3 Testing Procedure

3.3.1 Material and methods

Two types of clay, C1C and M44 were used for experiments in this research, which consisted pre-dominantly of Kaolin and Illite respectively. Preliminary research was carried out to find appropriate clays for testing. The objectives were firstly to test clays of different mineralogy; secondly to find clays that at least in their behaviour at room temperature were predictable by the modified Cam clay model (Roscoe and Burland, 1968), and finally to test a Smectite or Illite rich clay, similar to these previously considered as hosts for high-level nuclear wastes (Houston et al, 1985). Kaolin C1C was used because it had been previously investigated by Chiu (1996), and further tests were required to examine the validity of the results because of problems with the apparatus discussed above. It was decided not to proceed with tests on Smectite rich clay because

large quantities of Smectite would result in very slow drainage and long testing times, which was not viable with one way drainage. No supply of Illitic clay could be found in Australia at that time, and M44 Illitic clay was ordered from the USA. The detailed data sheet can be found in appendix 3.C. It was claimed by the manufacturer that the dominant mineral was Illite but X-ray diffraction (XRD) (Appendix 3.C) confirmed that the clay minerals, Illite and Kaolin, were equally dominant in the M44 clay, and comprised between 65% and 95% of the soil the remainder being mainly crystalline quartz. The XRD on C1C clay showed Kaolin as the main component (Chiu, 1996). Some properties of these two clays can be seen in Table 3.1. Preliminary tests at room temperature on both clays confirmed that both had plastic behaviour during undrained triaxial shear tests similar to that predicted by the Cam clay model.

3.3.2 Physical properties

The properties of Kaolin C1C were taken from past experiments done by Chiu (1996). The specific gravity of M44 clay was directly measured as the provided specification presented a wide range of 2.45-2.65 for specific gravity. The specific gravity was measured using the ASTM method D854-92. The average value was calculated to be 2.62. The Atterberg limits were also measured using ASTM method D4318-93.

Table 3.1 The properties of two types of clay were used in the current study

Type	Particle Size (%less than)	LL	PL	PI	Specific Area (m ² /g)
Kaolin C1C	99%<53 μ	63	32	31	-
M44	83%<5 μ	60	35	25	20.1

3.3.3 Procedure in permeability tests

The hydraulic conductivity tests were carried out during the time that the HTTA, high temperature triaxial apparatus was under modification. Therefore only tests at 22°C and 50°C were carried out.

3.3.3.1 Sample preparation

120 grams of M44 clay was thoroughly mixed with 120 ml of distilled de-aired water. The mixture was poured into a 50 mm diameter mould. Then it was pressed under a

dead load equivalent to 52 kPa and was left for 24 hours. After extrusion of the sample, the height and diameter were measured, and were about 47-50 mm and 50 mm respectively.

3.3.3.2 Sample setup and test procedure

The extruded sample was mounted in a modified triaxial machine as shown schematically in Figure 3.1. To saturate the sample a back pressure of 500 kPa was applied while the mean effective stress was kept constant at 30 kPa. B-values of bigger than 98% were measured before proceeding with the test. Two types of consolidation path were followed before performing the permeability test. In the first one the sample was isotropically consolidated to four different effective stresses of 200,300,400 and 600 kPa. After every increase in effective stress the permeability was measured by running a constant head permeability test (ASTM D5084-90). The second path was similar to the first path except that after the first stage the temperature was increased to 50°C with all the valves open to allow the drainage of pore water. Consolidation and permeability tests were conducted at 50°C. The temperature was reduced after last stage. During the permeability tests the cell pressure was kept constant. The pore pressure in the base of the sample was increased by 20 kPa while the pore pressure on the top was kept constant. The 20 kPa pressure difference was big enough to allow a constant flow of water from the bottom of the sample to the top. The volume change and pore pressure were continuously monitored by pore pressure transducers and two GDS. At the final step the sample was removed and its final dimensions and moisture content were measured.

3.3.4 Procedure in triaxial tests

3.3.4.1 Sample preparation

All samples were cylindrical and had a 50 mm diameter and a height to diameter ratio of between 2 and 2.2 after compression in the mould. A slurry of clay and distilled de-aired water was layered into a 50 mm diameter by 150 mm height brass mould. To facilitate moulding the slurries were made with water contents of 77% and 72% for samples of Kaolin C1C and M44 clay respectively. These values are about 1.2 times their respective liquid limits. Before moulding some petroleum jelly was applied to the mould's internal wall. During moulding all efforts were taken to prevent air being

trapped inside the sample. The mould was closed from both ends by filter papers and porous stones and then implemented with a top cap to apply load. The mould then was put under dead loads equivalent to 94 kPa for both clays. In a few cases the applied stress was increased to 110 kPa to get stiffer samples. At all times samples were kept under water. Samples were usually removed after 24 hours to be mounted in the triaxial machine.

3.3.4.2 Sample setup

Before mounting the sample all the drainage lines and the pore pressure transducer were filled with distilled de-aired water. Porous discs and all filter papers were saturated by soaking them in water and placing them under vacuum (28 mmHg) for 15 minutes. The filter papers used were Whatman no. 54 as they were found to be the most efficient for radial drainage and in order to have the maximum capacity of radial drainage during the long term triaxial tests the Whatman no. 54 has been reported to be the strongest and the most durable filter paper (Leroueil et al, 1988). In every test two 50 mm diameter circular and 4 strips of filter paper with 9.5 mm width each were used. The strips covered about 31% of the specimen periphery to avoid hoop tension and minimize the effect on the strength of soil. The first few triaxial tests on Kaolin used drainage from top and bottom. All subsequent experiments were carried out using radial drainage and only drainage from the base. For each test the sample was extruded manually and mounted directly on to the base of triaxial cell. Filter strips were placed on periphery of the sample with an angle of about 52 degree. A piece of circular filter paper was placed on the top of sample followed by the top cap. Then the specimen was covered with a membrane made of butyl rubber and sealed to the base and the top cap with six Viton O-rings. Internal LVDTs and proximity gauge targets were then put in place. Finally the cell cover was closed and was put into the oven and filled with the cell fluid, which was water. The experimental procedures are further discussed in chapter 4.

APPENDIX 3.A

DESCRIPTION OF PORE PRESSURE TRANSDUCER (PPT)

MODEL NO.	PH-50 KB
Manufacturer	Kyowa Ltd., Japan
Rated Capacity (R.C.)	10 to 500 kgf/cm ²
Safe Overload rating	120 % R.C.
Rated Output (R.O.)	2.2 mV/V
Non-linearity	0.4 % R.O.
Hysteresis	0.4 % R.O.
Excitation Voltage	(Max) 15 V
Bridge Resistance	350 Ω
Compensated Temperature Range	-196 °C to 200 °C
Safe Temperature Range	-196 °C to 220 °C
Temperature Effect on Zero Balance	0.03 % R.O./ °C
Temperature Effect on Output	0.03 %/ °C

DESCRIPTION OF DIFFERENTIAL PORE PRESSURE TRANSDUCER (DPPT)

MODEL NO.	P2144-0001
Manufacturer	Lucas Shaevitz
Input Voltage	10 VDC
Resistance	<10 Ω
Residual Unbalance(FRO)	$\pm 2 \%$
Output Voltage (BD)	$\pm 2.5 \text{ V} \pm 2 \%$
Thermal Zero Shift	$\pm 0.015 \%$ FRO/ $^{\circ}\text{C}$
Pressure Range	0-242 kPa
Differential Pressure Limit	
P1	1210 kPa
P2	483 kPa
Differential Burst Pressure	
P1	2416 kPa
P2	1450 kPa
Sensitivity Imbalance	$P_2 = P_1 \pm 2.5 \%$
Zero Shift with Alternating Full Range Pressure Cycling (BD)	$\pm 0.25 \%$ FRO on P_1 $\pm 0.5 \%$ FRO on P_2

DESCRIPTION OF PROXIMITY GAUGES (PG)

MODEL NO.	DT-18
Manufacturer	Sangamo, UK
Operating Range	0 to 5 mm
Maximum Range	0 to 6.5 mm
Case Material	300 series Stainless steel
Calibration Voltage	5 V rms
Calibration Frequency	5 KHz
Calibration Load	1 k Ω
DC Coil Resistance	162 Ω /coil
Input current, Open Gap	6.5 mA at 5 kHz, 5V
Temperature Range	-40 °C to +150 °C
Temperature Error	/100 < 5 % of 5mm (-10 °C to 100 °C) /150 < 5 % of 5mm (-10 °C to 150 °C)
Operating Pressure	0 to 7396 kPa

DETAILS OF LINEAR VARIABLE DIFFERENTIAL TRANSDUCERS (LVDT)

MODEL No.	D5/200AW/377
Manufacturer	RDP, UK
Linear Range	±5 mm
Maximum Range	0 to 11.5 mm
Sensitivity:	
LVDT No.1	63.32 mV/V/mm
LVDT No.2	61.93 mV/V/mm
Calibration Voltage	5V RMS
Calibration Frequency	5KHz
Linearity:	
LVDT No.1	0.15 %
LVDT No.2	0.32 %
Calibration Temperature:	
LVDT No.1	25 °C
LVDT No.2	21 °C

DETAILS OF INTERNAL LOAD CELL

MODEL No.	34/G570-01
Manufacturer	SENSOTEC
Capacity	4.5 kN tension
Excitation Voltage	10 V
Input Resistance	353 Ω
Output Resistance	353 Ω
Leakage	∞
Wiring Code:	
Red	(+) Excitation
Brown	(-) Excitation
Yellow	(-) Output
Orange	(+) Output

Digital Temperature Controller D series



Specifications

Input

Input (Universal input)	
a) Thermocouple :	K, J, R, S, B, E, T, N (JIS/IEC), PL11 (NBS) WRReW26Re (ASTM), U, L (DIN)
Influence of external resistance :	Approx. 0.4 μ V/ Ω
Input break action :	Up-scale
b) RTD :	PT100 (JIS/IEC), JPT100 (JIS)
Influence of input lead :	Approx. less than 10 Ω
Input break action :	Up-scale
c) DC low voltage input :	0 to 10mV, 0 to 100mV, 0 to 1V
Input break action :	Up-scale
d) DC high voltage input :	0 to 5V, 1 to 5V, 0 to 10V
Input break action :	Down-scale
e) DC current :	0 to 20mA, 4 to 20mA
Input break action :	Down-scale
A 250 Ω resistor is externally connected.	
Sampling time	
0.5 sec	
PV bias	
Temperature input : -1999(-199.9) to 9999(999.9) $^{\circ}$ C/ $^{\circ}$ F]	
DC voltage, DC current : -1999 to 9999(A decimal point position is the same as that of PV.)	

Performance

Measuring accuracy	
$\pm$ (0.3% of span + 1 digit)	
Cold-junction temperature compensation error	
Within $\pm 1.5^{\circ}$ C (between 0 and 50 $^{\circ}$ C [32 and 122 $^{\circ}$ F])	
Accuracy is not guaranteed between 0 and 400 $^{\circ}$ C (0 and 752 $^{\circ}$ F) for type B input.	
Accuracy is not guaranteed between 0 and 32 $^{\circ}$ F for type N, PL11 and WRReW26Re.	
Insulation resistance	
More than 20M Ω (500V DC) between input terminals and ground	
More than 20M Ω (500V DC) between power terminals and ground	
Dielectric strength	
1000V AC for one minute between input terminals and ground	
1500V AC for one minute between power terminals and ground	

Control

Control method	
a) PID control with autotuning and fuzzy logic	
b) Heat/cool PID control with autotuning and fuzzy logic	
Major setting range	
Setting range :	Same as input range.
Heat-side proportional band :	1(0.1) to setting limit high. (ON/OFF action when P=0)
Cool-side proportional band :	1 to 3000% of heat-side proportional band (Heat/cool ON/OFF action when P=0)
Integral time :	1 to 3600sec.(P + I action when I=0)
Derivative time :	1 to 3600sec.(P + I action when D=0)
Deadband/Overlap :	-10(-10.0) to 10(10.0) $^{\circ}$ C/ $^{\circ}$ F(Temperature input) -10.0 to 10.0% of span (Voltage, current input)
Proportional cycle time :	1 to 100 sec.
Output limiter high :	-5.0 to +105.0%
Output limiter low :	-5.0 to +105.0%
Manual control :	-5.0 to +105.0% (Heat/cool control type : -105.0 to +105.0%)
Control output	
Relay output :	Form C contact, 250V AC 3A (resistive load) (Form A contact : D100)
Voltage pulse output :	0/12V DC (Load resistance : More than 600 Ω)
* OUT1 of D400/D600 :	0/15V DC (Load resistance : More than 1K Ω)
Current output :	0 to 20mA, 4 to 20mA DC (Load resistance : Less than 600 Ω)
Continuous voltage output :	0 to 5V, 0 to 10V, 1 to 5V DC (Load resistance : More than 1K Ω)

Combination of output and type		OK : Available N/A : Not available	
Type	D100 Specify when ordering	D400/D600 (OUT1) Universal output	D400/D600 (OUT2) Specify when ordering
Relay contact	OK	OK	OK
Voltage pulse	OK	OK	OK
Current	OK	OK	OK
Continuous voltage	OK	N/A	OK

Alarm

Temperature alarm	
a) Number of alarms :	2 points
b) Alarm action :	Programmable (process, deviation, SV, FAIL)
c) Alarm differential gap :	-10 (-10.0) to 10 (10.0)
d) Alarm delay :	0 to 600 sec.
Control loop break alarm	
a) LBA time setting :	0 to 7200 sec. (LBA OFF by setting Zero)
b) LBA deadband :	0 to 999 $^{\circ}$ C ($^{\circ}$ F) or 100% of span (OFF by setting zero)
Output from ALM1 terminal OR output with temperature alarm is available. Not available for heat/cool control type.	
Heater break alarm (Optional)	
a) Number of inputs :	1 or 2 points (2 points for 3-phase heater)
b) CT type :	CTL-6-P-N (30A), CTL-12-S55-10L-N (100A)
c) Display range :	0.0 to 100.0A (OFF by setting Zero)
d) Accuracy :	$\pm$ 5% of input value or 2A (whichever is larger)
Output from ALM2 terminal OR output with temperature alarm is available.	
Alarm output	
Relay output, Form A contact 250V AC 0.5A (resistive load)	

Options

External contact input	
Number of inputs :	1 point
Type :	SV1/SV2 selection (open : SV1, close : SV2)
REX-D400/600 : Standard function, REX-D100 : Optional function	
Analog output	
a) Number of outputs :	1 point
b) Output signal :	0 to 5V, 0 to 10V, 1 to 5V DC (Load resistance : More than 1K Ω) 0 to 20mA, 4 to 20mA DC (Load resistance : Less than 600 Ω)
Output data can be selected among process value, deviation, set point, manipulated output value (heat-side or cool-side), current transformer input (With HBA function).	
Digital communications	
a) Communication method :	RS-485 (2-wire), RS-422A (4-wire)
b) Communication speed :	1200, 2400, 4800, 9600, 19200 bps
c) Bit format	Start bit : 1 Data bit : 7 or 8 Parity bit : Without, Odd or Even Stop bit : 1 or 2
d) Communication code :	ASCII(JIS) 7-bit code

General specifications

External Dimensions (W x H x D)	
D100 :	48 x 48 x 100mm
D400 :	48 x 96 x 100mm
D600 :	96 x 96 x 100mm
Supply voltage	
a) 90 to 254V AC (including supply voltage variation)	[Rating : 100 to 240V AC] (50/60Hz common)
b) 21.6 to 26.4V AC (including supply voltage variation)	[Rating : 24V AC] (50/60Hz common)
c) 21.6 to 26.4V DC (Ripple rate 10% p-p or less)	[Rating : 24V DC]
Power consumption	
D100 :	Less than 11VA (100 to 240V AC) Less than 7.0VA (24V AC)
D400/D600 :	Less than 180mA (24V DC) Less than 12VA (100 to 240V AC) Less than 7.5VA (24V AC) Less than 200mA (24V DC)
Effect by power failure	
A power failure of 20 msec or less will not affect the control action.	
Operating environments :	0 to 50 $^{\circ}$ C [32 to 122 $^{\circ}$ F], 20 to 80% RH
Memory backup :	Backed up by EEPROM.
Data retaining period :	Approx 10 years (depends on storage and operating conditions.)
Net weight	
D100 :	Approx. 180g
D400 :	Approx. 250g
D600 :	Approx. 350g



Model and Suffix Code

◆ REX-D100

Specifications	Model and Suffix Code
Model	D100 ☐ - ☐ ☐ * ☐ ☐ - ☐ ☐ ☐ ☐
Control method *2	PID control with AT Heat/cool PID with AT ☐ F ☐ W ☐
Control output (OUT1)	Relay output Voltage pulse DC mA, V (See output signal code table) ☐ M ☐ V ☐
Control output (OUT2)	No output (control method F) Relay output Voltage pulse DC mA, V (See output signal code table) ☐ N ☐ M ☐ V ☐
Alarm	No alarm Two alarms ☐ N ☐ D ☐
Heater break alarm(HBA) *1, *3	Not supplied Single-phase heater break alarm Three-phase heater break alarm ☐ N ☐ S ☐ D ☐
Contact input (Step) *1	Not supplied SV1/SV2 step function ☐ N ☐ 1 ☐
Analog output *1	Not supplied See output signal code table (Output signal code 4-8) ☐ N ☐
Digital communications *1	Not supplied RS-485 (2-wire system) ☐ N ☐ 5 ☐
Waterproof and dustproof (NEMA4X)	Not supplied Waterproof and dustproof protection ☐ N ☐ 1 ☐

*1 : One function can be selected from contact input, analog output, three-phase heater break alarm and digital communication.

*2 : If the heat/cool PID control with AT is selected, contact input, analog output, three-phase heater break alarm or digital communication can not be added.

*3 : If continuous voltage / current output is specified, no heater break alarm can be added.

For DC current input, a 250Ω resistor should be externally connected to the input terminals.

◆ REX-D400/900

Specifications	Model and Suffix Code
Model	D400 D900 ☐ - ☐ ☐ * ☐ ☐ - ☐ ☐ ☐ ☐
Control method *1, *2	PID control with AT Heat/cool PID with AT ☐ F ☐ W ☐
Control output (OUT2)	No output (control method F) Relay output Voltage pulse DC mA, V (See output signal code table) ☐ N ☐ M ☐ V ☐
Alarm	No alarm Two alarms ☐ N ☐ D ☐
Heater break alarm(HBA) /Step function	Not supplied (with step function) Single-phase heater break alarm (with step function) Three-phase heater break alarm (without step function) ☐ N ☐ S ☐ D ☐
Analog output *1, *2	Not supplied See output signal code table (See output signal code table) ☐ N ☐
Digital communications *2	Not supplied RS-422A (4-wire system) RS-485 (2-wire system) ☐ N ☐ 4 ☐ 5 ☐

*1 : If the heat / cool PID control with AT is selected, no analog output can be added.

*2 : If the heat / cool PID control with AT or analog output is selected, the digital communication function should be RS-485.

*3 : If continuous voltage / current output is specified, no heater break alarm can be added.

For DC current input, a 250Ω resistor should be externally connected to the input terminals.

Range and Input table

Thermocouple

Input	Range	Input	Range
K	-199.9 ~ 999.9 °C	B	0 ~ 1820 °C
	-200 ~ 1372 °C	E	0 ~ 3308 °C
	-199.9 ~ 999.9 °F	N	0 ~ 1300 °C
	-330 ~ 2500 °F	PLII	0 ~ 2372 °F
J	-199.9 ~ 999.9 °C	W28Re	0 ~ 2334 °F
	-200 ~ 1200 °C	U	0 ~ 800 °C
	-199.9 ~ 999.9 °F	L	0 ~ 1100 °F
	-330 ~ 2102 °F		0 ~ 900 °C
T	-199.9 ~ 400.0 °C		0 ~ 1600 °F
	-199.9 ~ 752.0 °F		
R	0 ~ 1789 °C		
S	0 ~ 3216 °F		

Output signal code table

4	0 - 5V DC	5	0 - 10V DC	6	1 - 5V DC	7	0 - 20mA DC	8	4 - 20mA DC
---	-----------	---	------------	---	-----------	---	-------------	---	-------------

How to specify safety standard

When you specify the models with CE mark • UL/CSA certification, please add the suffix of "/CE" to the model code.

RTD

Input	Range
JPt100	-199.9 ~ 510.0 °C
Pt100	-199.9 ~ 350.0 °F
	-199.9 ~ 660.0 °C
	-199.9 ~ 999.9 °F

Voltage and current

Input	Range
0 - 10mV	Scale range and decimal point are programmable in the range of -1999 to 9999.
0 - 100mV	
0 - 1V	
0 - 5V	
1 - 5V	
0 - 10V	
0 - 20mA*1	
4 - 20mA*2	

Current input

*1 For "0 - 20mA DC" input, a 250Ω resistor (±0.02% ±10PPM, more than 0.25W) is necessary to be connected externally to "0 - 5 V DC" input.

*2 For "4 - 20mA DC" input, a 250Ω resistor (±0.02% ±10PPM, more than 0.25W) is necessary to be connected externally to "1 - 5 V DC" input.

Supply voltage

100 - 240V AC

24V AC

24V DC

Please specify when ordering.

APPENDIX *3.B*

DESCRIPTION OF COM103C AND COM104C INTERFACE

COMMUNICATION LEVEL CONVERTER
FOR RS-232C/RS-422ACOM-103C
INSTRUCTION MANUAL

NOTE : Arrange that this manual will be handed to person in charge of the controller.

■ MOUNTING

1. Cautions for Mounting

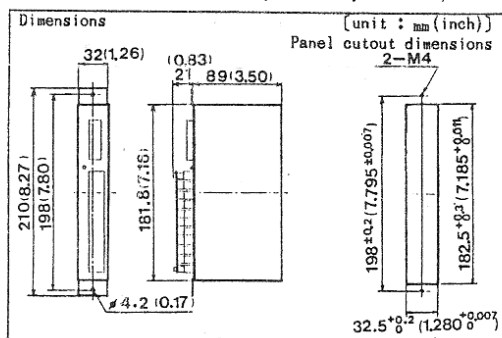
Avoid the following locations where the controller is mounted.

- ① Location where ambient temperature is more than 50°C (122°F) or less than 0°C (32°F).
- ② Location where much dust exists and where corrosive gas is generated.
- ③ Location where strong vibration and shock exist, where flooding and oil splash exist and where humidity is high.
- ④ Location where inductive disturbance is large and other location where bad influence is exerted on electric circuit.

2. Mounting

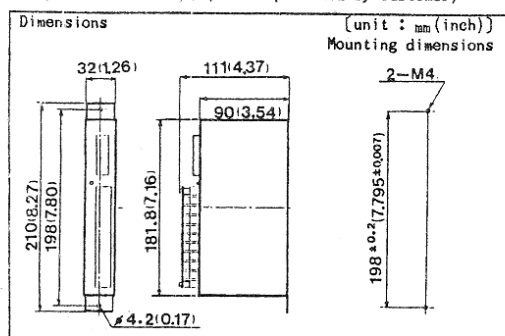
Rack mounting type (COM-103C-R)

- ① Make cutouts in the panel corresponding to the number of converters to be mounted by referring to panel cutout dimensions.
- ② Insert the converter into the cutout from the panel front.
- ③ Using a Phillips screwdriver, secure the converter from the terminal side with 2 setscrews (M4×6 SEMS pan-head screw). (Screws provided by customer)



Wall mounting type (COM-103C-W)

- ① Drill holes corresponding to the number of converters to be mounted by referring to panel cutout dimensions.
- ② Using a Phillips screwdriver, secure the converter from the terminal side with 2 setscrews (M4×6 SEMS pan-head screws). (Screws provided by customer)

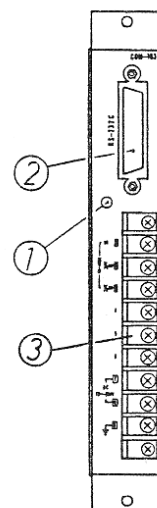


* Dimensions in inches are shown for reference.

Thank you very much for your purchasing our "COM-103C communication level converter for RS-232C/RS-422A". When it is delivered, check its external appearance and function to make sure that no damage exists. Do not touch or adjust other portions than those instructed in this manual.

This instrument is manufactured under strict quality control, and then is shipped. However, if there are any trouble found and suggestions to be made, contact your nearest agent or RKC.

■ NAME OF PARTS & TERMINALS



Terminal plate

Name of parts	
①. Power lamp	
②. Connector for RS-232C interface	
③. Terminals	
Terminals	
Terminals	Contents
1	SG Communication terminals
2	T/R(A) RS-422A
3	T/R(B)
4	
5	
6	
7	Power supply voltage terminals
8	AC 90 to 264V (including power supply variation)
9	Ground terminal

SG : Signal Ground
T/R(A) : Transmission Terminal (A)
T/R(B) : Transmission Terminal (B)

■ WIRING

• Cautions for wiring

1. Separate instrument power cable from electrical equipment power cable as much as possible to avoid an influence of noise.
2. In order to lessen a bad influence caused by noise, twist instrument power cables at close intervals. (The closer, the more effective.)

• Solderless terminals

Space of fitting a solderless terminal is 7.4mm×11.3mm (0.29inch×0.44inch). Therefore, use the solderless terminal suitable for a screw of M3.

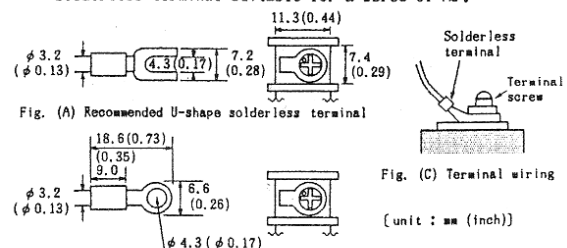


Fig. (B) Recommended round solderless terminal

Notes:

1. If the instrument has to be installed where there is large vibration or shock, be sure to use a round solderless terminal: a U-shape solderless terminal may happen to be slipped off from the terminal by vibration or shock.
2. If there is not enough space for wiring at the terminal, bend the solderless terminal as shown in figure (C).

IMCOMO4-E2

■ CONNECTION

This device supports communications between the RS-232C and RS-422A interfaces. When connecting to an other instrument, use the attached communication connector.

- ① Loosen the plug case screws, connect the cable core wires to the relevant connector pins, and mate the plug case with the wired connector before tightening the screws with a screwdriver.
(The cable is provided by the customer.)
- ② Plug the communication connector connected with the cable ① into the instrument connector (See the terminal plate diagram.)
- ③ Then, using a screwdriver, secure the connector with 2 upper and lower screws.

Accessories

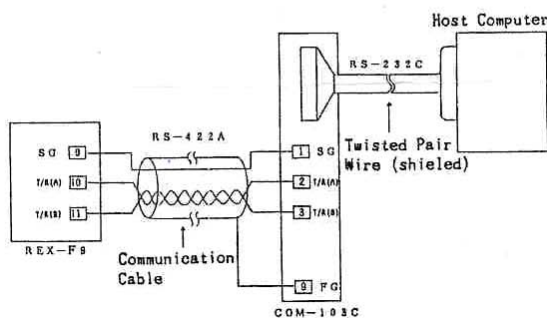
Connector ...HDBB-25P (Hirose Electric Co., Ltd. or equivalent)

Plug case ...HDB-CTF (Hirose Electric Co., Ltd. or equivalent)

Also, for connecting with the other instrument based on RS-422A communication, to use a twisted pair wire (shielded) under referring "NAME OF PARTS & TERMINALS" and "WIRING". (The twisted pair wire should be prepared by the user.)

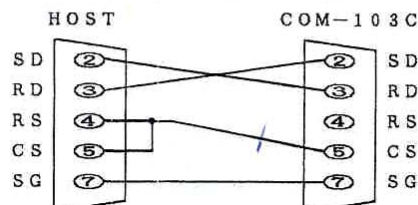
■ CONNECTION EXAMPLE

This is a connection example for using our instrument "REX-F9".

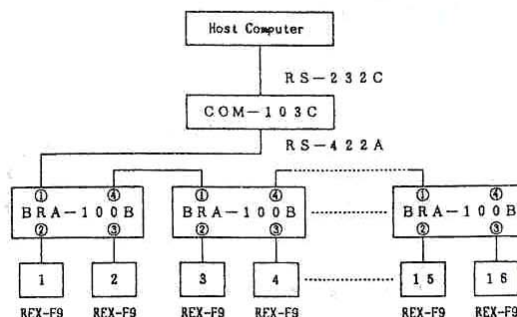


REX-F9 is an instrument with communication function in accordance with RS-422A (based on EIA Specifications). Therefore, it is connectible with a host computer which has RS-232C interface by use of COM-103C. Host computer and COM-103C are connected by a cable for RS-232C (using the connector). Also COM-103C and REX-F9 are connected by a twisted pair wire (shielded). (using the terminals #1, #2, #3 of COM-103C.)

Communication cable for RS-232C
(close connection for RS-232C)

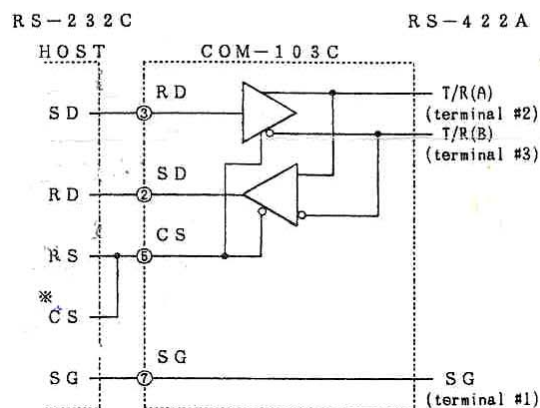


This is the application on using "REX-F9" and "BRA-100B".



Because REX-F9 is a temperature controller capable of connection up to maximum 16 sets, if branched with our instrument BRA-100B, the transmission distance between COM-103C and BRA-100B may be extended to some degree and multi-drop connection becomes possible.

■ INTERNAL CONNECTION



- ※ ON : Output the data of RS-232C side to RS-422A side.
- OFF : Output the data of RS-422A side to RS-232C side.

For details of RKC's REX-F9 and BRA-100B, see their catalogs.

RKC. RKC INSTRUMENT INC.

IMCOM04-E2

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PHONE: 03-751-8111 (+81 3 751 8111)
TELEX: 0246-8818 RKCTOK J
CABLE: RKCRIKAROL
FAX: 03-754-3316 (+81 3 754 3316)

NOV. '87

DETAILS OF CIO-DAS1600 A/D BOARD

POWER CONSUMPTION			DIGITAL I/O		
+5	2.1A MAX,	1.4A Typical	Input/Output	24 bits	8255, three 8 bit ports
+12	Not Used		Input only	4 bits	74LS244
-12	Not Used		Output only	4 bits	74LS197
ANALOG INPUT - CIO-DAS1600/12			Input low volts	74LS244	0.8V MAX
Channels	8 Differential	16 Single Ended		8255	0.5V MAX
Resolution	12 Bits	1 part in 4095	Input high volts	74LS244	2.0V MIN @ 20uA
Accuracy	0.01% of reading, ± 1 bit			8255	2.0V MIN, 7.0V MAX
Input Range	$\pm 10V$ MAX	$\pm 0.25V$ MIN	Output low volts	74LS197	0.5V MAX @ 8.0mA
Coding	See table in section on Analog Input			8255	0.5V MAX @ 2.5mA
	Bipolar	Offset binary	Output high volts	74LS197	2.4V MIN @ -0.4mA
	Unipolar	True binary		8255	2.4V MIN @ -200uA
Overvoltage	$\pm 35V$ continuous		INTERRUPT		
Input Current	250 nA MAX	12 nA typ @ 25 deg C	Level	2-7	Software programmable
Input Impedance	10 Meg Ohm		Enable	INTE Bit	CIO-DAS1600 Control register
Temp. Coeff.	Full Scale	± 25 ppm/deg C MAX	Trigger	On board	8254 pacer clock
	Zero	± 12 ppm/deg C MAX		External	User supplied TTL pulse
Type	Successive Approximation		DMA A/D TRANSFER		
Conversion Time	3.3 uSec MAX	ADS7800	Level	1 or 3	Switch selectable
Monotonicity	Guaranteed over operating temp. range.		Enable	DMA Bit	CIO-DAS1600 Control register
Linearity	± 1 Bit		Termination	Single Cycle	Interrupt on terminal count
Zero drift	± 10 ppm/deg C MAX			Recycle	
Gain drift	± 30 ppm/deg C MAX		Pacing	Internal	8254 pacer clock
Vref Output	-5V $\pm 0.05V$			External	User supplied TTL pulse
ANALOG INPUT - CIO-DAS1600/16			POWER OUTPUTS		
Only specifications which differ from DAS1600/12			Direct from PC bus		See your PC spec.
Resolution	16 Bits	1 part in 65,535	Voltage	$\pm 5V \pm 5\%$	Depends on PC power
Accuracy	± 1.5 LSB		Loading	22AWG	64.9 Ohms/ 1000 feet
Conversion Time	10.0 uSec MAX	ADS7805	ENVIRONMENTAL		
Monotonicity	Guaranteed over operating temp. range.		CIO-DAS1600 Normal Temp Model		
Linearity	-1, ± 0.5 LSB		Operating Temp	0 to 50 Deg C	
Zero drift	± 2 ppm/deg C MAX		Storage Temp	-20 to 70 Deg C	
Gain drift	± 7 ppm/deg C MAX		Humidity	0 to 90% non-condensing	
D/A CONVERTERS			Weight	11.2 Oz	
Channels	Two Independent		CIO-DAS1600 Extended Temp Model		
Type	12 bit multiplying, double buffered		Operating Temp	-30 to 60 Deg C	
Linearity	± 1 bit		Storage Temp	-165 to 150 Deg C	
Monotonicity	± 1 bit		Humidity	0 to 90% non condensing	
Output range	$\pm 10V$ MAX		Weight	10.25 Oz	
Output drive	$\pm 5mA$ MIN				
Output resistance	<0.1 Ohm				
VREF Input range	$\pm 10V$				
Full scale out	Gain = -1 * VREF				
Settling time	30 uSec to 1% for full scale step.				
PROGRAMMABLE TIMER					
Type	82C54				
Counters	3, 16 Bit down counters				
	2 dedicated to A/D pacer				
XTAL	1 or 10 MHz				
Output Drive	2.2mA @ 0.45V				
Input	TTL				
Frequency	DC to 10MHz				
Active count edge	Negative				
Clock pulse width	30nSec High	50nSec Low			

DESCRIPTION OF PC73 A/D TEMPERATURE BOARD

- A/D resolution: 12 Bits + sign
- Non linearity: Less than ± 0.75 LSB
- A/D full scale input ranges: -40.95 to + 40.95 mV, -4.095 to 4.095 V, -20.475 to 20.475 mV and -8.190 to 8.190 mV jumper selectable.
- Number of A/D inputs: 8 differential thermocouple inputs, one cold junction compensation input.

- A/D throughput rate: 30 Hz

Host interface

The PC-73 is accessed via I/O operations performed by the host processor. Of the 10-bit address received by the board, the most significant 8 bits select the board, and the least significant 2 bits select the register to be accessed. The PC-73 occupies four byte locations. The base address of the PC-73 is switch selectable from 100H to 3FCH. The PC-73 operates from the + 5V, + 12V and -12V lines of the PC bus.

DESCRIPTION OF OD5 SIGNAL CONDITIONER

Common Specifications			
Power Supply		Oscillator/Demodulator	
Power Supply	250V AC 50-60Hz or 120V AC 50-60Hz	Oscillator frequency	2.5 or 5kHz Sinusoid
		Oscillator output voltage	3V rms
		Oscillator max. current	20mA
Loading	4W (Max.)	Input sensitivity for rated output	Lo 35 to 1000mV/V Hi 17 to 500mV/V
Fuse Rating	@ 250V 63mA Slow Blo @ 120V 63mA Slow Blo	For Rated Output	Lo 5 to 140mV/V Hi 110 to 290mV/V
Mechanical		Output	±5V into 10KΩ ±20mA into 100Ω maximum
Case Size	130mm x 96mm x 35mm	Output Zero Offset	0 to ±100% adjustable
Weight	400g	Output protection	Output open/short circuit protected
Mounting	Two (2) Fixing Bars	Output ripple @ 5kHz 250Hz filter	<10mV pk/pk at 10kHz
Termination	5-Pin DIN Connector	Output filter	2nd order low pass fc at 250Hz or 110Hz
		Non-Linearity	Less than 0.05% of rated output
		Temperature range	0 - 60°C
		Temperature Coefficient	Max
		Overrange 0 - 60°C	<0.02% frol/°C
		Zero Gain	<0.02% frol/°C
			Typical
			<0.01% frol/°C
		Oscillator protection	will withstand open CCT or short CCT of oscillator

Table C1.1

Instruments Referred to by this Manual	
Part Number	Description
911134	OD5 LVDT Conitioning Unit

Table C1.2

APPENDIX 3.C

M44 typical data Sheet

Raw Properties

Crude Color	Grey
Dry Modulus of Rupture (psi)*	700
Wet Sieve Residue, +200 mesh (%)	1.00
Plasticity (%)	35
Linear Drying Shrinkage (%)	7.5
Soluble Sulfates (ppm)	640
Filtration (ml)	16
Specific Surface Area (m²/g)	20.1
CEC/MBI (meq/100 ml)	11.0
PH	6.0
Particle Size (%less than)	
5 Micron	83
1 Micron	62
0.5 Micron	52
Median Particle Diameter (Micron)	0.45

*50% clay/50% flint, castbars

Chemical Analysis	%
Silicon Dioxide (SiO₂)	59.38
Aluminum Oxide (Al₂O₃)	26.51
Iron (Ferric) Oxide (Fe₂O₃)	1.32
Titanium Oxide (TiO₂)	1.51
Calcium Oxide (CaO)	0.18
Magnesium Oxide (MgO)	0.37
Sodium Oxide (Na₂O)	0.12
Potassium Oxide (K₂O)	0.82
Loss on Ignition	9.79

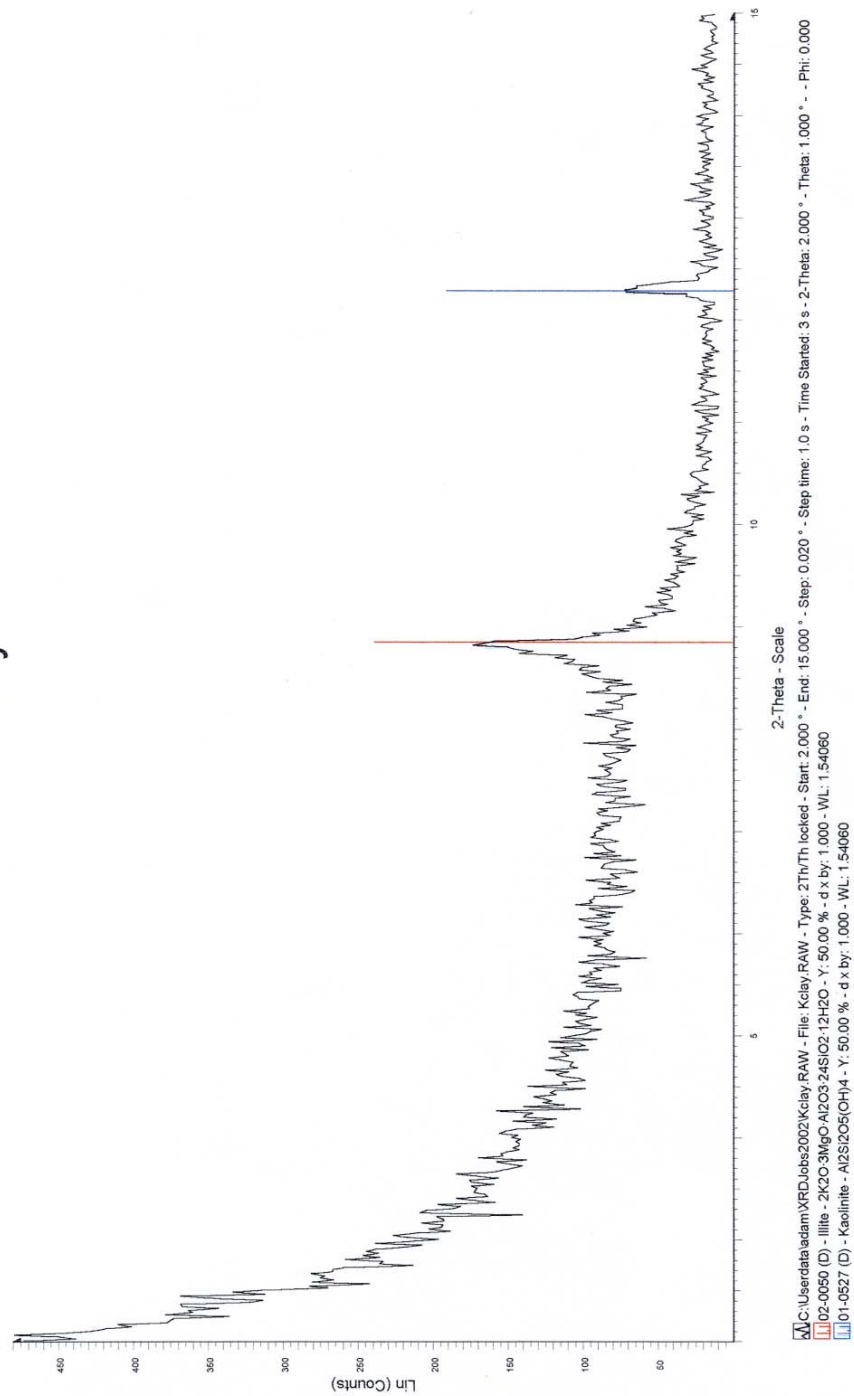
FIRED PROPERTIES	Cone 4	Cone 3	Cone 11
Linear Fired Shrinkage (%)	5.6	6.0	6.4
Absorption (%)	9.1	6.7	2.5
PCE	31		

Kaolin C1C typical data Sheet

Chemical Analysis	%
Silicon Dioxide (SiO₂)	51
Aluminum Oxide (Al₂O₃)	33.8
Iron (Ferric) Oxide (Fe₂O₃)	0.7
Titanium Oxide (TiO₂)	0.8
Calcium Oxide (CaO)	0.2
Magnesium Oxide (MgO)	0.5
Sodium Oxide (Na₂O)	N/A
Potassium Oxide (K₂O)	0.3
Loss on Ignition	13.4

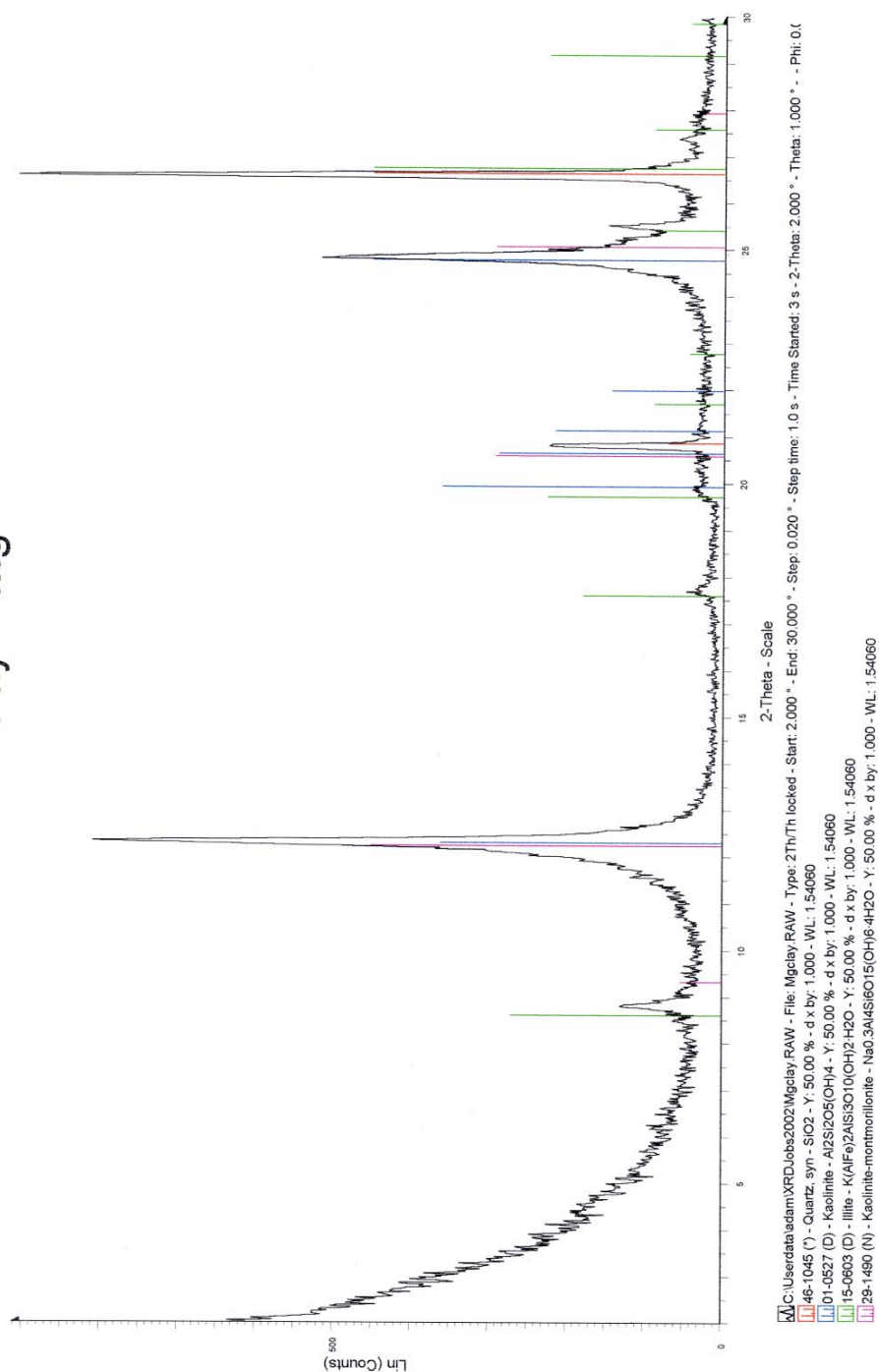
Specific Gravity	2.6
Oil Absorption (ml/10g)	5.5
Water Absorption (ml/10g)	4.5
Moisture (%)	1.5
PH	7.5
Particle Size (%less than):	
150 Micron	100
75 Micron	99.9
53 Micron	99

M-44 clay - K

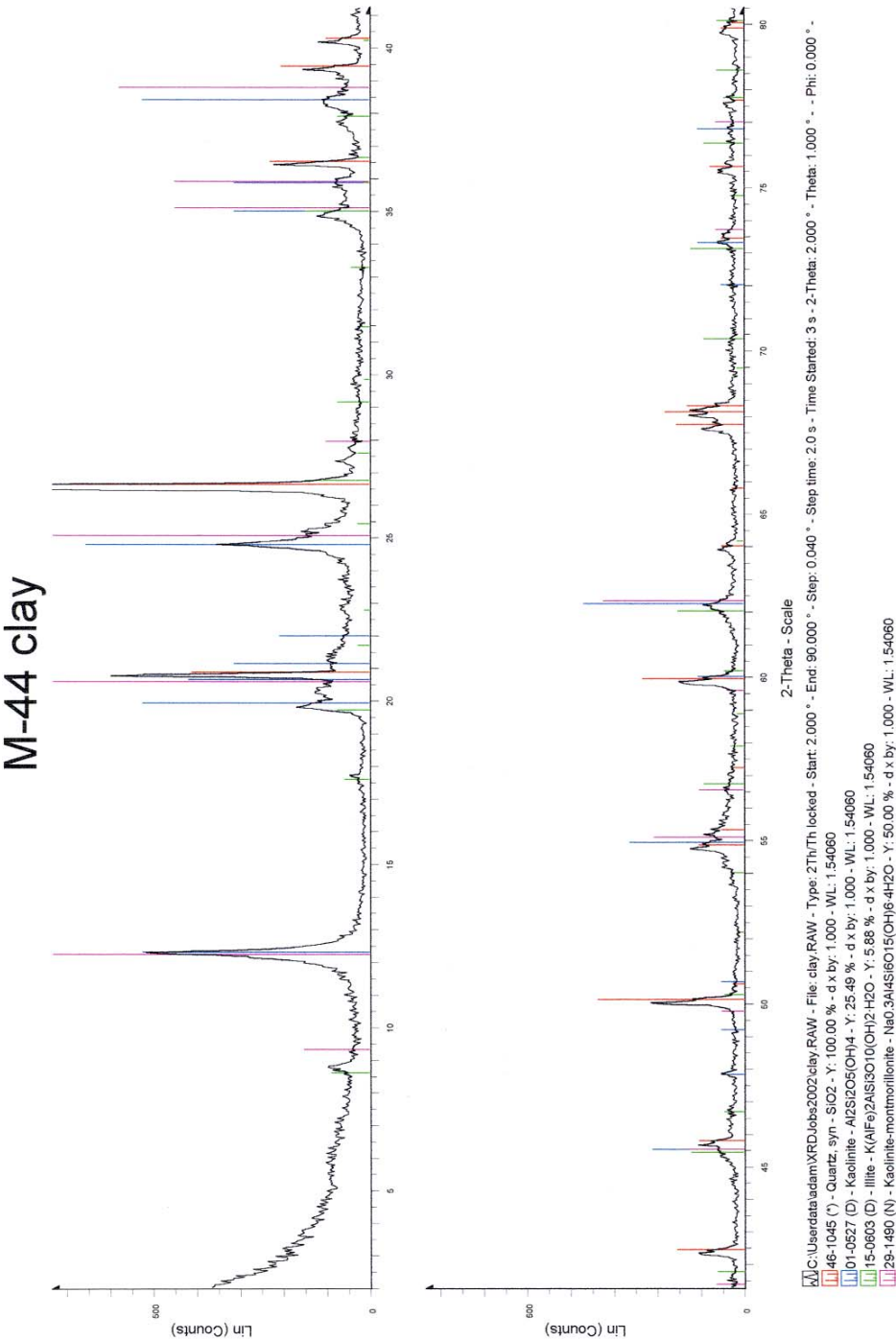


The Result of XRD on modified sample of M44 clay to target Illite

M-44 clay - Mg



The Result of XRD on modified sample of M44 clay to target Kaolin



The Result of XRD on raw M44 clay powder

4

CHAPTER

THERMO-MECHANICAL BEHAVIOUR OF CLAY

4.1 Introduction

In order to investigate the behaviour of clay at various temperatures a number of different tests were carried out on remoulded samples of two types of clay, Kaolin C1C and Kentucky M44 Clay. At the beginning some properties of both clays such as specific gravity, liquid limit and plastic limit were measured at room temperature. Then the stress-strain responses of both soils were investigated at temperatures between 22°C and 100°C by performing drained and undrained triaxial tests on normally and over consolidated samples. The properties of Kaolin C1C at different temperatures were previously investigated by Chiu (1996), but as discussed previously a leak in the connections was detected, and this may have compromised the data. Testing of the same clay was performed firstly to check the equipment and repeat some of his data, and secondly to compare with the findings of M44 clay. The results at different temperatures are compared to explain the effects of consolidation path on the stress-strain response of the clay. In addition to the triaxial experiments, the hydraulic conductivity of M44 clay was directly measured at temperatures up to 50°C.

In this chapter, the experimental procedures, data analysis, the method of corrections and finally the results will be discussed.

4.2 Triaxial testing of saturated clay at various temperatures

Sample preparation and setup, and triaxial apparatus were thoroughly discussed in chapter 3. This section presents details of the test procedure.

4.2.1 Experiment procedure

Each sample was subjected to some or all of the following steps:

- Saturation
- Drained or undrained heating
- Isotropic consolidation
- Over consolidation
- Undrained or drained shear test

4.2.1.1 Saturation

Before starting saturation the loading ram was brought into contact with the sample top cap several times to permit proper seating and alignment of ram with the cap. Care was taken to not apply an axial load bigger than 0.5% of the estimated axial load at failure (ASTM, D4767). The reading of the external LVPT was recorded when the ram was in touch with the top cap as a reference point. Subsequently, the variations of sample height can be determined from both the LVPT and the internal LVDTs. An initial cell pressure of 80 kPa was applied while the drainage line was kept closed. The pore pressure stabilized at different values under the 80 kPa cell pressure and then drainage was allowed to the back pressure GDS controller which was set to 0 ± 1 kPa. This test procedure caused some consolidation of the samples because the mean effective stress was greater than the previous effective stress during one-dimensional consolidation in the mould and also had the effect of removing some of the effects of one-dimensional consolidation. The saturation was carried out by applying back pressures of 200 kPa and 500 kPa for tests at room temperature and elevated temperatures respectively. These values were found to be big enough: (1) to drive all the air into solution for soft clay (Bishop and Henkel, 1962), and (2) to prevent pore water from boiling at temperatures higher than 100°C (Steam Tables). The back pressure was increased by ramping both cell and back pressures with a rate of about 0.5 kPa per minute while keeping the effective stress constant at 80 kPa. This rate was slow enough to prevent any undesirable pre-stressing or over consolidation. After saturation Skempton's pore pressure parameter B was calculated from the following relationship:

$$B = \frac{\Delta u}{\Delta \sigma_3} \quad (4.1)$$

Where Δu is the change in the pore pressure as result of a change in the cell pressure, $\Delta \sigma_3$, while drainage is not allowed. The B value in all cases was between 95% and 100%.

4.2.1.2 Consolidation

In order to investigate the effects of consolidation history on the mechanical behaviour of the soil during shearing, several consolidation paths varying from simple to very complex were applied to the specimens. Four different paths, shown in Figure 4.1, were followed to produce isotropically normally consolidated specimens. Path A, depicted in Figure 4.1(A), involves the sample being mechanically consolidated to a certain effective stress at point 2, followed by a slow temperature increase while drainage is allowed. Path B is similar to path A except that the sequence of mechanical and thermal consolidation is changed. In path C, like path A mechanical consolidation takes place first followed by undrained heating that increases the pore pressure and reduces the effective stress (keeping p constant). Then the drainage is allowed so that the effective stress returns to its value before heating at point 4. Path D involves stages of mechanical and thermal consolidation at different temperatures.

For overconsolidated samples five different paths E, F, G, H and I shown schematically in Figure 4.2, were examined. Paths E and F are the same except that the sequences of heating, consolidation and over consolidation are different. In path E the sample is mechanically consolidated from point 1 to point 2 (Figure 4.2E), then the effective stress is reduced to overconsolidate the sample, and then slow drained heating takes place. Paths G and H are respectively comparing the effects of cyclic undrained and drained heating on normally consolidated and overconsolidated samples. In path I, the sample is mechanically consolidated to point 2 then the sample is heated under undrained conditions to point 3. After reaching equilibrium the drainage valve is opened so the sample is consolidated to point 5. Finally, the sample is over consolidated to point 6 by reducing the effective stress. It should be noted that thermal expansion has been shown in Figures 4.2E and 4.2H, to accompany heating at high OCRs as reported by Baldi et al (1988). Whether expansion or contraction occurs is to be determined by experiment.

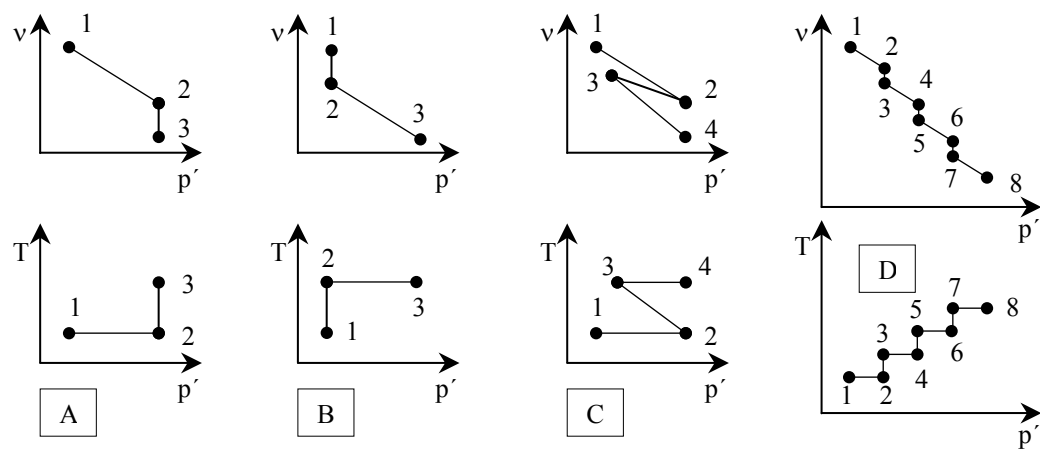


Figure 4.1 Isotropic normally consolidation paths for Triaxial testing

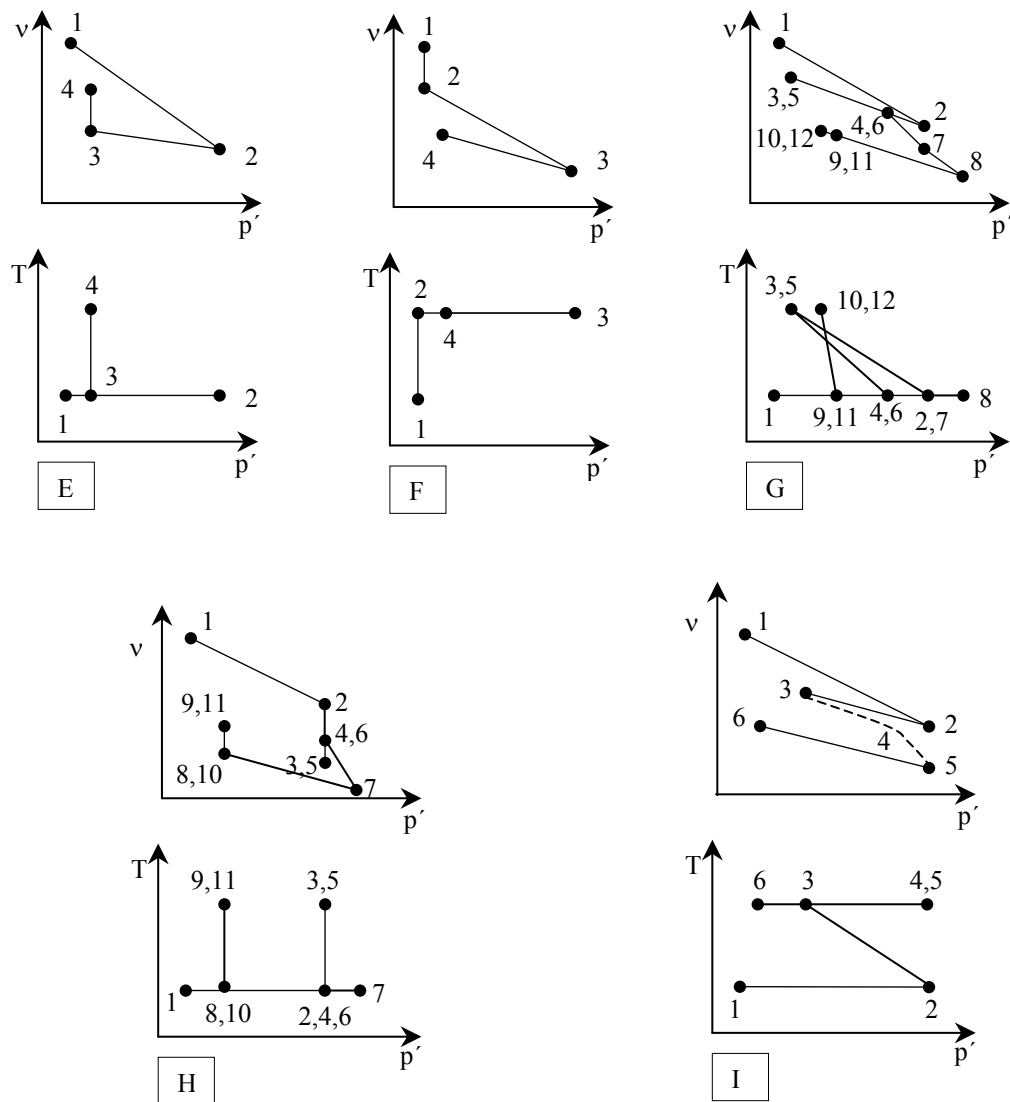


Figure 4.2 Paths were used to over consolidate the samples

4.2.1.3 Shear

Drained and undrained shear tests were performed at room temperature (22°C), 50°C, 75°C and 100°C. During shearing the cell pressure was kept constant while the loading ram was driven down using a standard displacement rate controlled loading system. Before starting undrained shear the drainage line to the sample was closed at the tap inside the oven and pore pressure was measured by the pore pressure transducer. Prior to shearing the loading ram was lubricated with silicon oil and was brought into contact with the top cap to allow proper seating and realignment of the ram with top cap. The maximum rate of loading was calculated using the method presented by Bishop and Henkel (1962) which is based on the type of drainage. As has been mentioned in chapter 3, Leroueil et al (1988) clearly demonstrated that the efficiency of filter strips used for radial drainage is over estimated by Bishop and Henkel's approach. Therefore, some tests were carried out to investigate the efficiency of radial drainage and the results confirmed Leroueil et al's findings. These results are reported in appendix 4.A. In order to prevent any rate effects on strength or stiffness of the sample the selected loading rate in most cases was less than the calculated values. The average loading rates during undrained and drained shearing were 0.01 and 0.002 mm/min respectively. The method of calculation is also discussed in appendix 4.A. These rates were slow enough to allow the equilibrium of pore pressure during undrained tests and to permit dissipation of pore water during drained tests. It should be mentioned that Chiu (1996) used loading rates of 0.03 and 0.003 mm/min for undrained and drained shear tests on samples of Kaolin C1C respectively (having drainage from both ends). When a sample failed, the drainage lines to the sample were closed and temperature was decreased to room temperature. Then the sample was removed and quickly weighed before being placed in an oven to dry. After 24 hours when the sample was dried, it was weighed again and the final moisture content was measured.

4.2.1.4 Primary calculations and data analysis

The final dry and wet masses of the samples were used to calculate the specific volume of the sample by dividing the total volume of the specimen by the volume of the solids. Changes in the volume of the specimens were measured internally by displacement transducers and externally by the GDS controller to calculate the specific volumes of the samples at different stages. At all times the calculated volumes were corrected for

changes in temperature. As discussed in chapter 2 the density of water is a function of temperature and this was considered during calculations.

The following relationships were used for determination of specific volume v :

$$v = \frac{V_w + V_s}{V_s}, V_s = \frac{w_s}{G_s \times \rho_w}, V_w = \frac{w_w}{\rho_w} \quad (4.2)$$

where ρ_w is the density of water, V_s and V_w are the volumes of solid and the volume of water respectively, w_w is the weight of water, w_s is the weight of solid and G_s is the specific gravity of solid.

The height of the specimen after mechanical and thermal consolidation, H_c , is determined from the changes measured by either internal or external LVDTs subtracted from the initial height, H_o . The cross sectional area of the sample after consolidation, A_c , was calculated using the following equation:

$$A_c = \frac{V_w f_w + V_s f_s}{H_c} \quad (4.3)$$

where V_w is the volume of water in the specimen after consolidation (this volume is based on the final water content and the amount of water drained during shear considering the thermal volume change of water in the drainage tubes), f_w and f_s are correction factors for thermally induced changes in the volume of water and volume of soil particles respectively. These factors are further discussed in the next section.

The axial, volumetric and shear strain, ϵ_a and ϵ_v and ϵ_s , were calculated from the following formulas:

$$\epsilon_a = \frac{\Delta H}{H_c} \quad (4.4)$$

$$\epsilon_v = \frac{\Delta V}{V_c} \quad (4.5)$$

$$\epsilon_s = \epsilon_a - \frac{\epsilon_v}{3} \quad (4.6)$$

where ΔH is the change in sample height during shear measured by the LVDTs, H_c is the specimen height after consolidation, ΔV is the change in sample volume during a drained shear test, V_c is the volume of specimen after consolidation. The axial stress was computed by dividing the axial load by an effective area. It was assumed that the

samples deformed as right cylinders. So the cross sectional area, mean effective stress and deviator stress were calculated using the following relationships:

$$A = A_c \left(\frac{1 - \varepsilon_a}{1 - \varepsilon_v} \right) \quad (4.7)$$

$$q' = \sigma'_1 - \sigma'_3 = \frac{F}{A} \quad (4.8)$$

$$p' = \frac{\sigma'_1 + 2\sigma'_3}{3} \quad (4.9)$$

$$\sigma'_3 = \sigma_3 - u \quad (4.10)$$

A_c is the average cross-sectional area after consolidation, q is the deviator stress, F is the given applied axial load, A is the corresponding cross-sectional area, σ_3 is the cell pressure, σ'_1 and σ'_3 are the effective major and minor principal stresses respectively, u is the induced pore water pressure at the given axial load.

4.2.1.5 Corrections and errors

Filter drain resistance

The spiral drains used in this experimental study were assumed to be perfectly flexible and hence require no correction (Germaine and Ladd, 1988).

Membrane resistance

As has been mentioned in chapter 3, a butyl rubber membrane with the thickness of around 0.7 mm has been used to isolate the sample from the cell water. This will create resistance against sample deformation. Therefore, the following equation (ASTM, D4767) was used to correct the effects of membrane resistance on the deviator stress:

$$\Delta(\sigma'_1 - \sigma'_3) = \frac{4E_m t_m \varepsilon_a}{D_c} \quad (4.11)$$

$\Delta(\sigma'_1 - \sigma'_3)$ is the correction to be subtracted from the measured deviator stress, E_m is the Young's modulus for the membrane material, t_m is the thickness of the membrane, ε_a is axial strain (in decimal form) and D_c is the diameter of the specimen after consolidation. The membrane resistance causes an increase of approximately 10 to 15 kPa in the calculated deviator stress for an axial strain of 10%. Measurement of the membrane modulus was discussed in chapter 3.

Temperature corrections

Variation of temperature will cause error in the volume change measurement, expansion of drainage lines and changes in the calibration of transducers. As discussed in chapter 3 all transducers, measuring devices and volume changes in the drainage lines were calibrated to allow for changes in temperature. The correction for expansion of water in the sample and changes in the volume of soil particles were determined using the following equations:

$$V'_w = V_w f_w \quad (4.12)$$

$$V'_s = V_s f_s \quad (4.13)$$

$$f_s = 1 + \alpha_s \Delta T \quad (4.14)$$

$$f_w = 1 + a_w \Delta T \quad (4.15)$$

V'_w and V'_s are corrected values of volume of water and volume of solids due to temperature change (ΔT), and α_s is the volumetric coefficient of thermal expansion of solid. In order to derive f_w the variations in α_w , the coefficient of thermal expansion of free water, with temperature are plotted in Figure 4.3. The data has been taken from the tabulated water properties provided by Chapman (1974). The value of α_w changes almost linearly with temperature between 22°C and 100°C and the relationship can be written as:

$$\alpha_w = 6.899 \times 10^{-6} T + 9.788 \times 10^{-5} \quad (4.16)$$

Combining 4.12, 4.15, and 4.16, and rearranging the following equation is obtained:

$$\frac{dV_w}{V_w} = (6.899 \times 10^{-6} T + 9.788 \times 10^{-5}) dT \quad (4.17)$$

Integrating over the range of temperature change, the volume of water is given by:

$$V'_w = V_w \text{EXP}[3.45 \times 10^{-6} (T^2 - T_0^2) + 9.79 \times 10^{-5} (T - T_0)] \quad (4.18)$$

where T is the temperature at the end of consolidation (°C), T_0 is the initial temperature (°C). Comparing 4.18 and 4.12 leads to:

$$f_w = EXP[3.455 \times 10^{-6}(T^2 - T_o^2) + 9.79 \times 10^{-5}(T - T_o)] \quad (4.19)$$

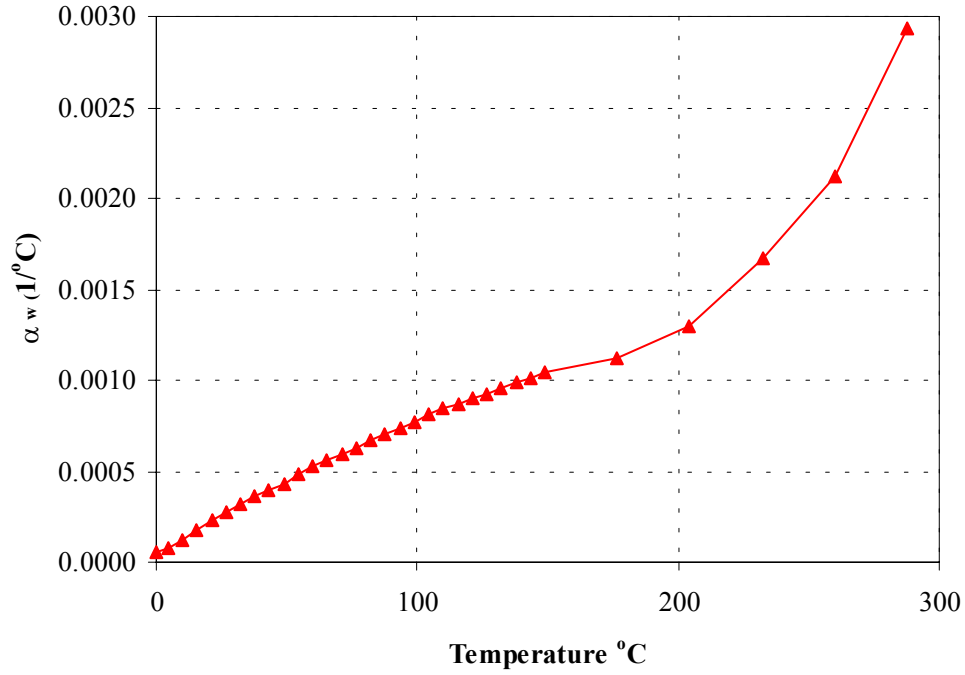


Figure 4.3 Changes in α_w with temperature (after Chapman, 1974)

4.2.2 Results of tests on M44 clay

4.2.2.1 Isotropic mechanical and thermal consolidation

It has been mentioned in section 4.2.1.2 that different thermo-mechanical consolidation paths were examined in order to investigate the effects of consolidation history on the stress-strain behaviour of clay. The variations in specific volume with temperature and mean effective stress, p'_c , during thermo-mechanical consolidation of M44 clay from all tests are reported in a Table in appendix 4.B. The Table includes sample number, p'_c , specific volume at different temperatures and comments regarding the consolidation process.

In most cases, the effective stress was changed incrementally with a rate of between 0.1 to 0.25 kPa per minute. This rate was slow enough to ensure negligible pore pressure build up. In order to find the shape of the thermal compression curve, the temperature was raised under drained conditions with a rate of 0.1°C per minute in steps of 10°C to 15°C. In other words, the temperature was raised from 22°C to 35°C then 50°C, 65°C, 75°C, 85°C and 100°C. After reaching each temperature, enough time was given for equilibrium to be reached. The variations of temperature (measured in the centre of

sample) and drained volume of water with time for sample (HTUO17) during drained heating are shown in Figure 4.4. It can be seen that at each step equilibrium has been achieved before heating to the next higher temperature, and the rate of heating has not exceeded a maximum of 0.09°C per minute (determined from the graph). The curve of volume change shows some creep at the end of each stage that seems to be similar at different temperatures.

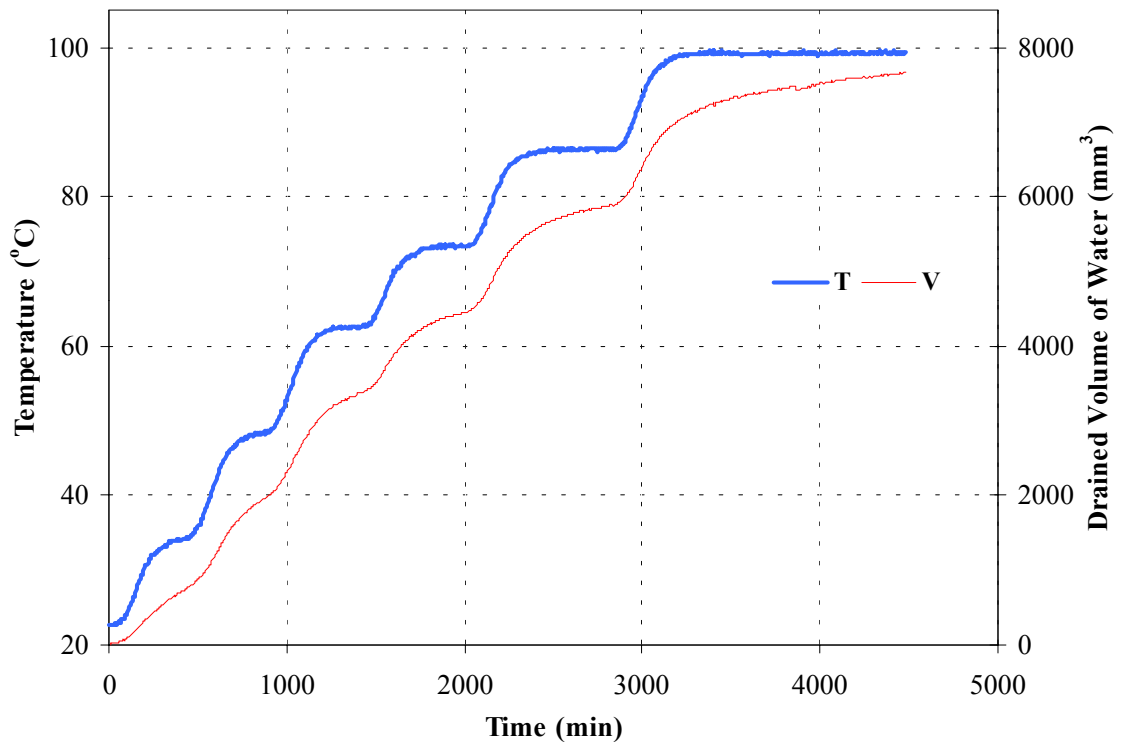


Figure 4.4 Variations of temperature with time during thermal consolidation of sample HTUO17

During thermal unloading (cooling), the temperature was dropped in stages from 100°C to 75°C then 50°C and finally 27°C (the minimum temperature that could be reached in 10 hrs time). Figure 4.5 demonstrates the first cycle of heating and cooling of sample HTUO17. At the start of this cycle the sample was normally consolidated (NC) and had not experienced elevated temperatures. The continuous red curve shows the specific volume changes versus temperature. The dashed line connecting the ends of the heating steps illustrates the shape of the thermal compression curve (TCC) in the v - T plane, which can be described by a second order polynomial. However, if allowance is made for the different times for creep in the various steps the TCC might be considered linear

for practical purposes. The green and blue curves show the subsequent cooling and heating cycles. It is found that v is changing linearly with temperature during unloading-reloading (cooling-reheating) cycles. This graph is typical of the NC samples, and the amount of thermal contraction has been found to be practically independent from stress level for p' between 80 kPa and 400 kPa. Similar results have been reported by other researchers (e.g. Demars and Charles 1982, Campanella and Mitchell 1968).

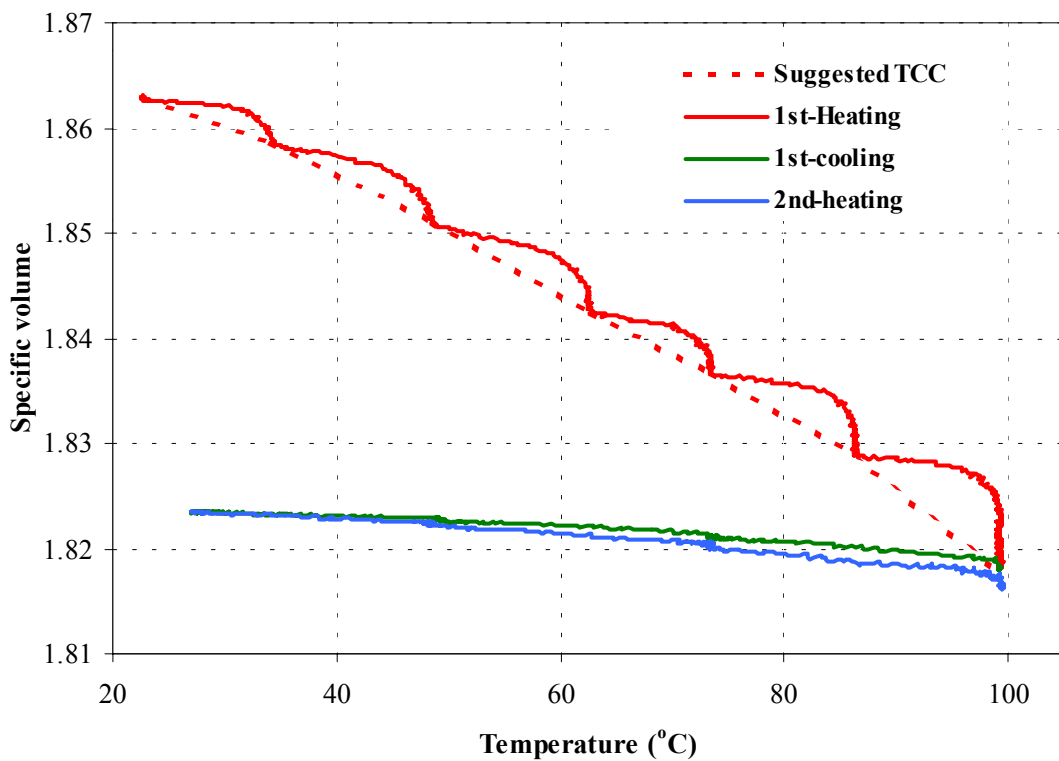


Figure 4.5 Thermal compression of M44 clay (Based on data from GDS)
($p' = 400$ kPa)

In addition, it is noticeable that the deformation of NC samples during drained heating is mainly plastic and is not recoverable in subsequent cooling. The observed bumpy response seen in Figure 4.5 is similarly observed in the data determined from the LVDT's readings indicating that this is "real" soil behaviour and not an artefact of the corrections applied to the volume change readings. The reasons for this type of response are not clear at this stage but it might be related to the rate of heating or non-uniform temperature gradient within the sample. It should be noted that the process of heating

from 22°C to 100°C took about 75 hours (see Figure 4.4) to complete, and the whole test on sample HTUO17 (including preparation, saturation, consolidation and shearing) took about one month to complete. So further reduction in the rate of heating did not seem to be practical. The time required for temperature equilibrium in a 50 mm diameter specimen of Kaolin C1C subjected to an increase in temperature from 22°C to 150°C has been reported to be 66.15 minutes (Chiu, 1996). The time to reach thermal equilibrium for samples of M44 clay should be similar to Kaolin C1C, as their thermal conductivities are believed to be similar. The small separation between the reheating and cooling curves in Figure 4.5 suggests that the volumetric changes during thermal swelling can be treated as predominantly elastic. Much larger differences between the cooling and reheating curves (Figure 4.5) have been reported by other researchers (e.g. Campanella and Mitchell 1968) and it has been suggested that these derive from physico-chemical reactions in the sample. The specific volume increases during cooling from 100°C to 22°C but this should not be interpreted as expansion because the relationship between volumetric strain and changes in specific volume is given by:

$$\varepsilon_v = (1 + \alpha_s \Delta T) \frac{v_2}{v_1} - 1 \quad (4.20)$$

For contraction ($\varepsilon_v < 0$): $v_2 < \frac{v_1}{1 + \alpha_s \Delta T}$ and not simply $v_2 < v_1$.

For expansion ($\varepsilon_v > 0$): $v_2 > \frac{v_1}{1 + \alpha_s \Delta T}$ and not simply $v_2 > v_1$.

The complete consolidation path of sample HTUO17 in the v - T plane, which is identical to path H (Figure 4.2), is shown in Figure 4.6. Prior to drained heating, the sample had been mechanically consolidated to $p'_c = 400$ kPa then as shown in Figure 4.5, the sample was incrementally heated up to point 2 followed by two cycles of cooling-heating before reaching point 5. Then the sample was mechanically consolidated to $p'_c = 500$ kPa (6) and unloaded to $p'_c = 200$ kPa (7). Then one cycle of heating and cooling was carried out before the sample was sheared at 100°C (point 10). The blue and red lines show the calculated values of v from GDS and LVDTs (assuming isotropy) respectively. Although the results from the GDS and LVDTs are different in terms of magnitude, the slopes of the cooling-reheating lines in the v - T plane are apparently similar in normally consolidated (2-3-4) and lightly

overconsolidated ($OCR = 2.5$) parts (8-9-10) except that the latter is shifted upwards as a result of mechanical unloading between points 6 and 7. Comparison of this phenomena with the swelling line in the v - p' plane suggests that any heating and cooling on the thermal swelling line is purely elastic. An elastic response would be expected from the volume changes of solid particles during temperature change so contraction is expected during cooling and expansion during reheating. From point 7 to 8 the strain is greater than the "elastic" response, suggesting that mechanical over consolidation at 22°C has resulted in partial removal of the effects of the previous thermal cycles. As mentioned earlier the small increase observed in specific volume during cooling should not be interpreted as expansion (see equation 4.20). In other words, the changes in specific volume in some cases may not reflect the real volume changes in the sample. This has been clearly identified by plotting the volumetric strains versus temperature in Figure 4.7. The volumetric strain is presented in a way that contraction is positive while expansion is negative in sign.

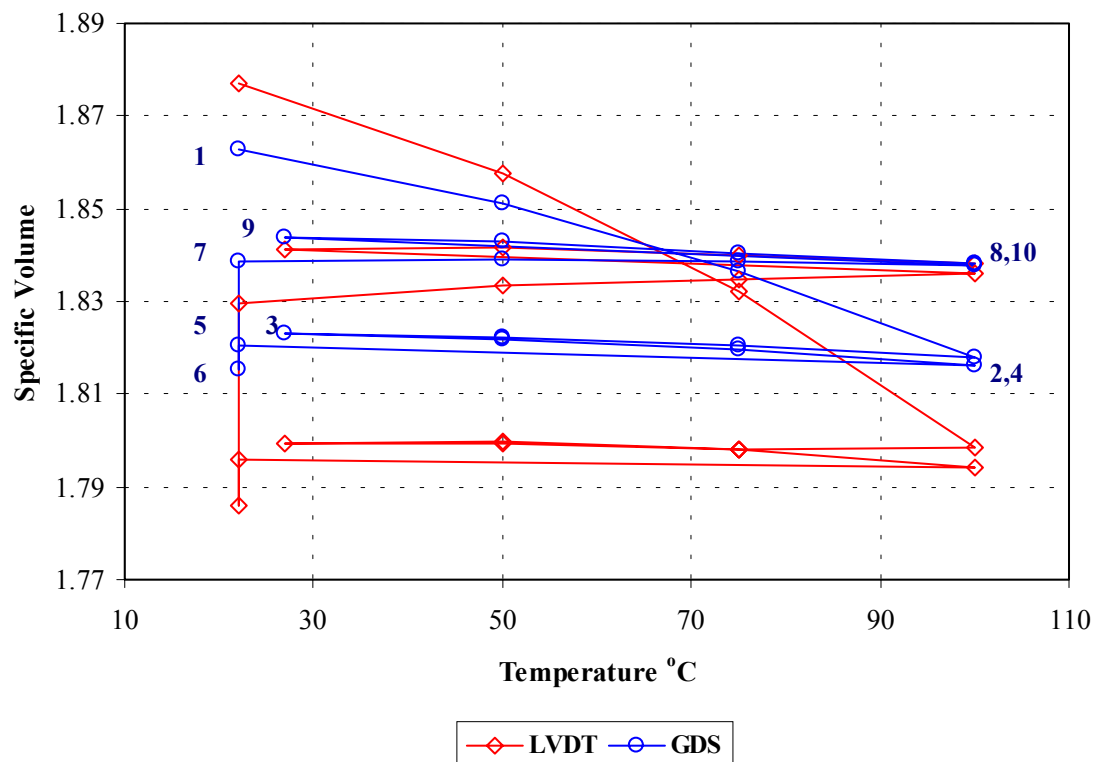


Figure 4.6 Results from cyclic drained heating of sample HTUO17

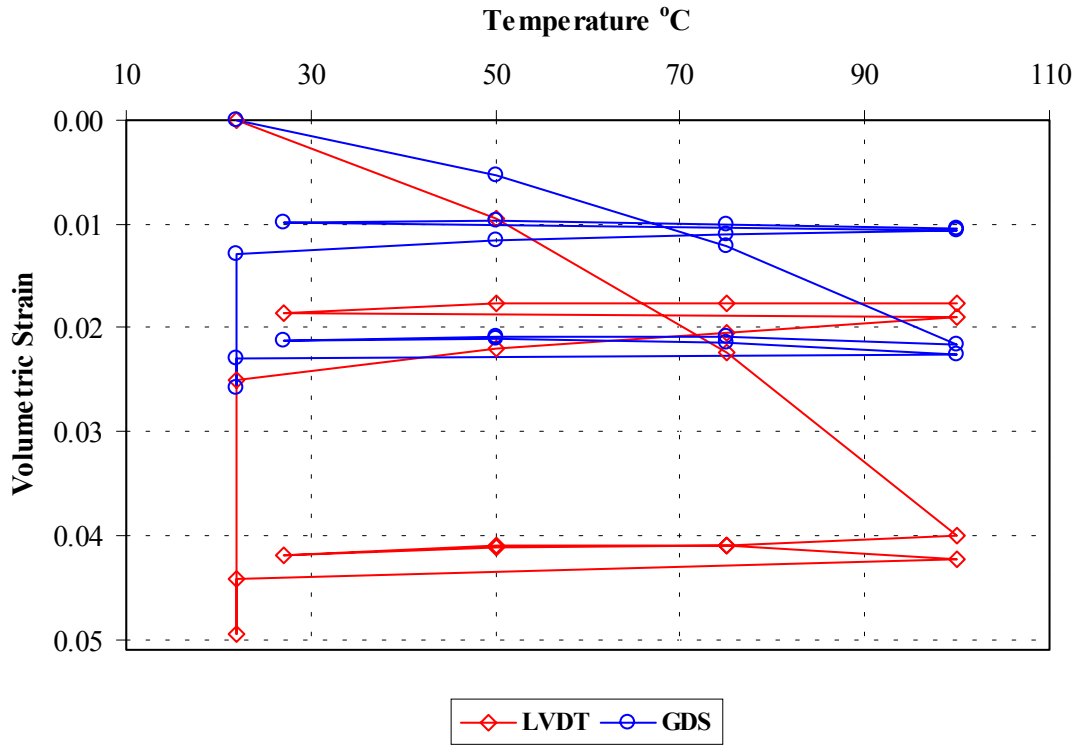


Figure 4.7 Variations of volumetric strain with temperature for sample HTUO17

It can be seen that during cooling-reheating the slopes of the volumetric strain and specific volume responses with temperature have different signs. It can also be seen from the graph that the total volumetric strain determined from the GDS and the LVDTs are 2.2% and 4% respectively. This difference could be a consequence of the isotropy assumption used to estimate ε_v from the ε_a measured by the LVDTs, or an error in the volume corrections for the GDS at elevated temperature. Examination of the consolidation data at room temperature indicates that this difference is more likely to be the result of error in the assumption of isotropy. Unfortunately the radial strains could not be measured accurately of the two proximity gauges, one stopped working just after the first experiment, and the second one was available for only a few tests at elevated temperature. Figure 4.8 demonstrates the variations of volumetric and radial (ε_r) strains, determined from the GDS and one PG respectively, with changes in axial strain calculated from the LVDTs at room temperature for tests RTUO15 and RTUN14. The PG was not available during the test RTUO15 therefore the ε_r - ε_a curve was drawn using the results of test RTUN14. Essentially identical responses were observed in all room temperature tests.

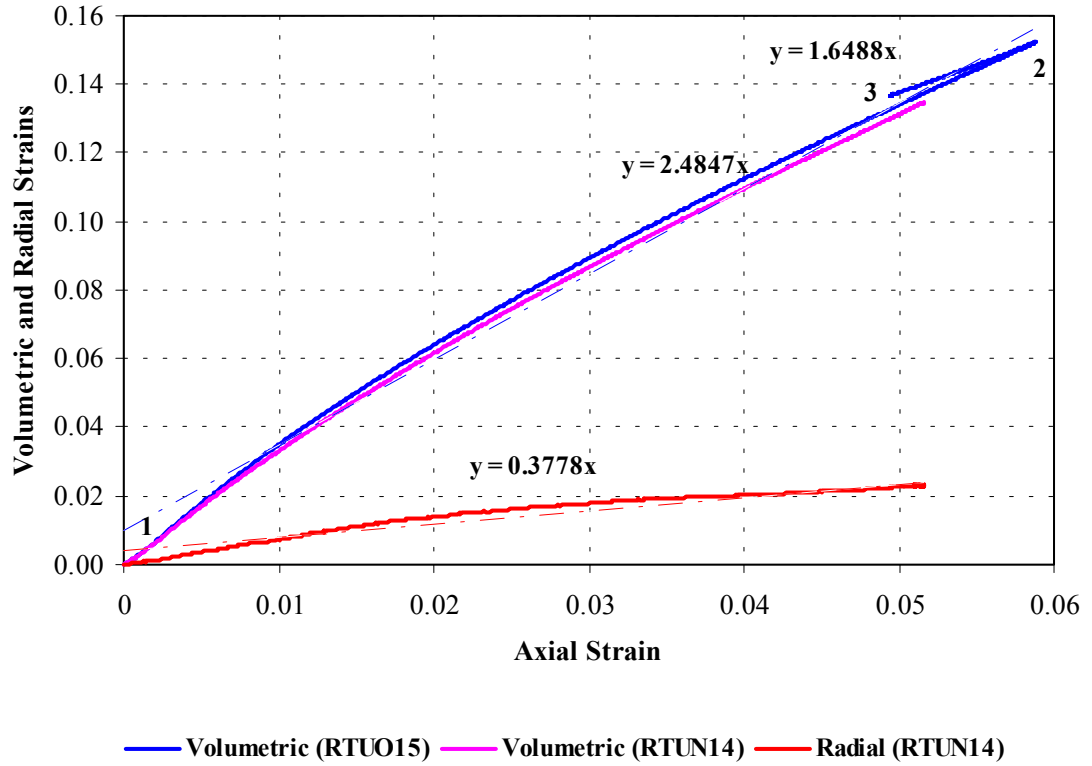


Figure 4.8 Comparison between ε_v (GDS), ε_r (PG) and ε_a (LVDT) at room temperature

As can be seen, both volumetric and radial strain curves at the beginning of consolidation have a higher slope than the end of consolidation. The equations on the graph present the average slope of each curve by drawing the best-fit line through the data points using a least squares method. The average slope of volumetric strain, ε_v , curve during mechanical consolidation (1-2) is 2.48 and implies that the assumption of $\varepsilon_v = 3\varepsilon_a$ is not always true and can be used for soft clay only during a certain part of consolidation when the strains are small. This slope is even lower, 1.65, during mechanical over consolidation (2-3) resulting in a greater difference between volumetric strains determined from the LVDTs and the GDS controller. Similarly the average slope of radial strain curve determined from one proximity gauge is about 0.38 during consolidation while according to the isotropy assumption it should be equal to one. This difference might be partly related to the measurement of radial displacement only at one side of the sample as this could have been affected by tilting during consolidation of the sample or by the misalignment of the PG's target. However, in all but one test the data from the single PG lay in a small band suggesting that tilting had not significantly

influenced the data. The available proximity gauge was properly functioning only in 3 tests at elevated temperature and therefore only indirect determination of the volumetric strains at elevated temperature could be carried out using the LVDTs. The over estimation of volumetric strain by the LVDTs shown in Figure 4.7 is a consequence of the isotropy assumption during drained heating-cooling cycles. These cycles were carried out after mechanical consolidation to 400 kPa, at which ε_v (from the GDS) $\approx 2.1\varepsilon_a$ (from the LVDTs). By using this relationship instead of assuming isotropy ($\varepsilon_v = 3\varepsilon_a$) the determined value of volumetric strain from the LVDTs during heating of sample HTUO17 from 22°C to 100°C (1-2) will reduce from 4% to 2.8%, closer to the GDS determined value shown in Figure 4.7. It can be noted that with application of a proper conversion factor the volumetric strain can be reasonably predicted from the axial strain determined from the LVDTs. The conversion factors during consolidation from $p' = 80$ kPa to $p' = 500$ kPa have been extracted from Figure 4.8 and are reported in table 4.1 at different effective stresses.

Table 4.1 Estimated factors from Figure 4.8 to convert axial strains to volumetric strains

p' (kPa)	80	200	300	400	500
$\varepsilon_v/\varepsilon_a$	3.78	2.76	2.27	2.1	2.08

The volumetric strain during cooling from 100°C to 22°C (2-3, 4-5 in Figure 4.7) has been calculated to be 0.04% expansion from the GDS and 0.2% contraction from the LVDT measurements. In the lightly OC state ($OCR = 2.5$) the value determined from the LVDTs reduced to 0.1% expansion while it remained the same for the GDS. Although it has been shown that the LVDTs over estimate the volumetric strain (if isotropy is assumed) during mechanical consolidation and overconsolidation they appear to provide a more reasonable trend during cooling-reheating than the GDS indicating contraction upon cooling and vice versa. The thermal volumetric strain due to contraction of solid particles during cooling from 100°C to 22°C is expected to be about 0.15% ($\sim 250 \text{ mm}^3$) considering $\alpha_s = 0.35 \times 10^{-4}$ (reported by Campanella and Mitchell, 1968). A volume change of 250 mm^3 is very small and can be easily ill-estimated from the GDS because of the various volume corrections for temperature change. As a result, during small deformations at elevated temperature the LVDTs results have been used for the calculations of volumetric strain applying a relevant conversion factor from

figure 4.8. Ignoring the slight variations observed in the slopes of thermal swelling curves, it might be considered that the thermally induced volume changes along these curves are reversible and purely elastic. These variations might be related to the time dependant behaviour of M44 clay at elevated temperature that is discussed later.

Figure 4.9 shows the variations of volumetric strain with temperature for sample HTDN20. This is one of the limited tests in which the PG was properly functioning. The sample was initially heated up from 22°C to 75°C at $p' = 80$ kPa before mechanical consolidation to $p' = 400$ kPa. It can be seen that the thermal volumetric strains determined from the internal instruments (the LVDTs and one PG) are in good agreement with those determined from the GDS and if the volumetric strain is calculated from the LVDTs alone using the factor from Table 4.1, in this case $\varepsilon_v = 3.78\varepsilon_a$ instead of $\varepsilon_v = 3\varepsilon_a$ (isotropy assumption), it will be very close to the results obtained from the GDS. Therefore it is expected that reasonable determination of volumetric strain can be determined from the LVDTs.

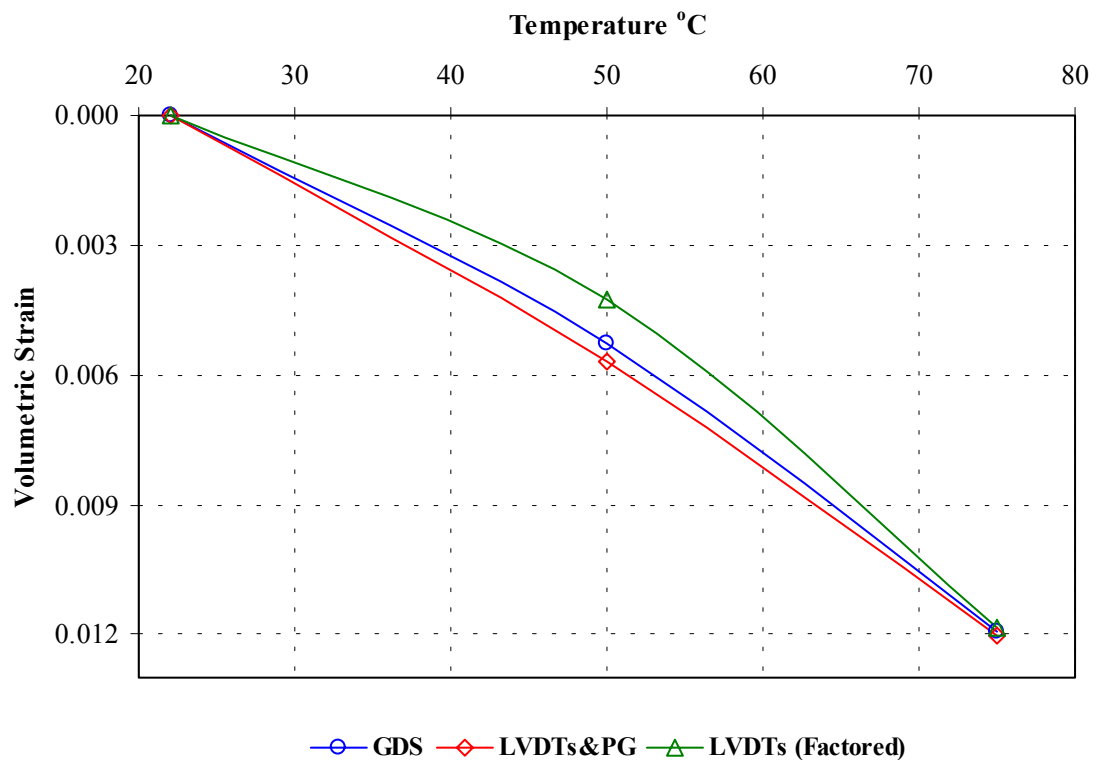


Figure 4.9 Variations of volumetric strain with temperature for sample HTDN20

Highly overconsolidated (OC) samples have shown a different response from NC and lightly OC samples to drained heating as typically demonstrated in Figure 4.10. The volumetric strains estimated by the LVDTs here have been obtained using a conversion factor of 1.65 for over consolidated samples (see Figure 4.8). The volumetric strains in this case have been slightly overestimated by the LVDTs. This may be because the conversion factor of 1.65 is for a sample with $OCR = 2.5$ and with initial maximum effective stress of $p' = 500$ kPa, whereas in Figure 4.10 the OCR and maximum p' are 7 and 700 kPa respectively. There were no room temperature tests with similar stress histories, which had made use of internal measurements to extract the exact conversion factor. It can be seen from Figure 4.10 that the sample dilated about 1.25% (LVDT) upon heating from 22°C up to about 80°C then started to contract. As was mentioned earlier in the literature review this conversion from expansion to contraction has been also reported by other researchers (e.g. Baldi et al 1988, Towhata et al 1993b). It has been shown by Baldi et al that higher OCRs resulted in higher temperatures for the expansion-contraction changeover point.

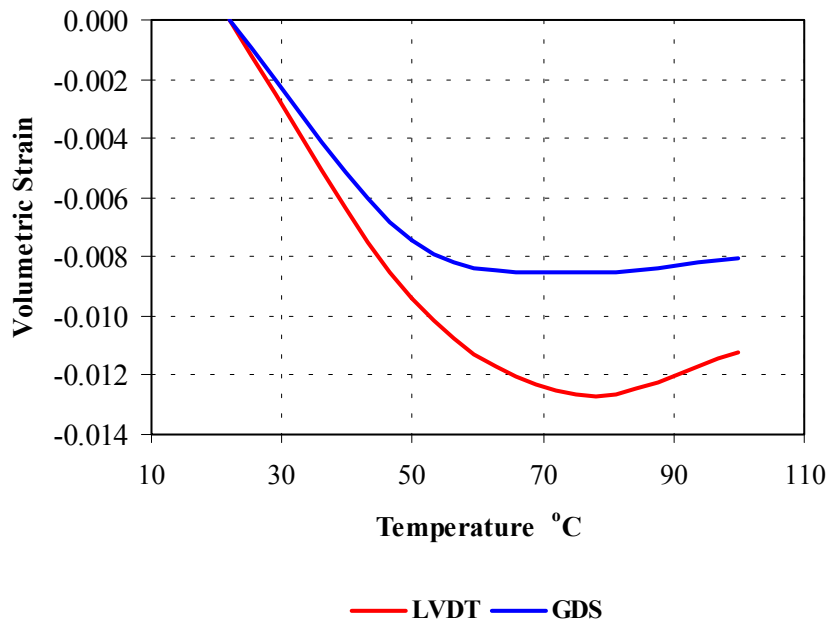


Figure 4.10 Variations in drained thermal volumetric strain for OC samples ($OCR = 7$)

Figure 4.11 displays results of mechanical compression and swelling of M44 clay in the v - p' plane. The rate of change in the confining stress was 0.2 kPa/minute. Sample

RTUO15 was consolidated to an effective stress of 500 kPa at 22°C then overconsolidated to 200 kPa implying an OCR of 2.5. Sample HTUO14 was consolidated to $p'_c = 700$ kPa and unloaded to 100 kPa then heated up to 100°C. Sample HTUO15 has an identical stress history to HTUO14 except that the consolidation and swelling stages have taken place at 100°C. It is often considered that the relationship between specific volume and natural logarithm of mean effective stress is linear, but by careful examination of the data shown in Figure 4.11 it can be noticed that the slope of the swelling curve, κ , is increasing as the effective stress reduces. For the purpose of comparison, it is important to draw the swelling lines from the effective stresses at the end of each mechanical loading to effective stresses at which they all present an OCR of 2.5. The graph shows that the slope of this line, κ , decreases with temperature. It has reduced from 0.0335 at 22°C to 0.0275 at 100°C. Further support for this hypothesis is given later by results of tests on Kaolin C1C.

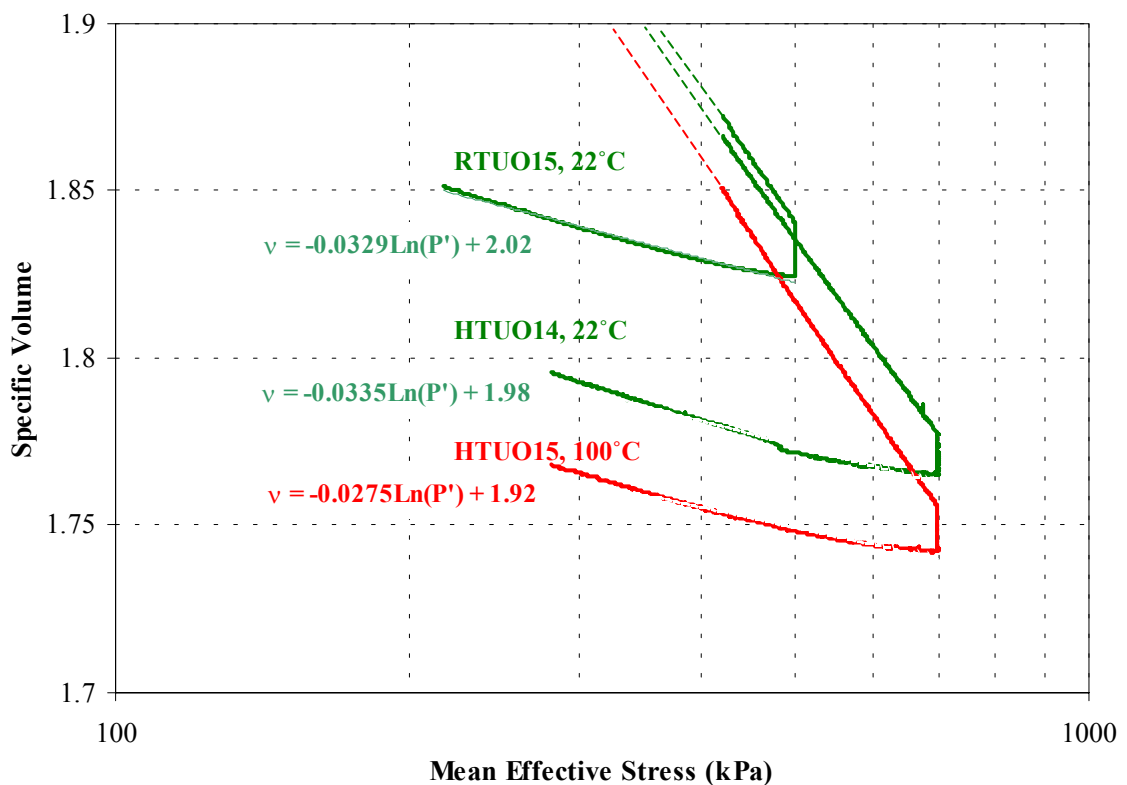


Figure 4.11 Isotropic swelling lines at 22°C and 100°C

In order to study the pore pressure response of M44 clay, path G in Figure 4.2 was applied to sample HTUO16 and the results are shown in Figure 4.12. The test has two

parts, undrained cycles of heating and cooling (22-100°C) when the sample was initially normally consolidated, and similar cycles after the sample had been mechanically overconsolidated. In the first stage the sample was isotropically consolidated from p' of 80 kPa to 400 kPa then it was subjected to two cycles of heating and cooling. After cooling down to 27°C drainage was allowed and it was mechanically consolidated by increasing the mean effective stress to 500 kPa. Then it was mechanically overconsolidated by reducing p' to 200 kPa. Finally, the specimen was subjected to two cycles of undrained heating and cooling. Drainage was then permitted at the end of the last cycle before the sample was sheared under undrained conditions. Figure 4.13 shows that in both cyclic stages the effective stress reduces with temperature rise because the temperature induces an increase in the pore pressure. In addition, there is a slight residual pore pressure build up evident in the second cycle for both stages of heating and cooling. In other words, the value of effective stress reduces from 400 kPa to 118 kPa when temperature is increased from 22°C to 100°C but due to the residual pore pressure only reaches 346 kPa when the sample is cooled back down to 22°C. When the sample is heated up again to 100°C p' decreases to 100 kPa, which is 18 kPa lower than in the first cycle and in the subsequent cooling period p' reaches 341 kPa, which is only 5 kPa different from the previous cycle. Although no further cycles were performed it appears that the pore pressure response will rapidly stabilise. A similar pattern is shown for the initially overconsolidated stage, but with negative residual pore pressures and the effective stress higher after the second cycle of heating and cooling. The results are consistent with those obtained from drained heating as in the NC state sample HTUO17 developed a slight contractive volume strain after cycles of heating and cooling compared to positive residual pore pressure build up here. Whereas in the OC state, sample HTUO17 presented expansive volume strain in agreement with the negative residual pore pressure build up in sample HTUO16. It is believed this behaviour is related to creep. The time dependant behaviour of M44 clay is further discussed later in this chapter. A residual pore pressure build up was not observed by Campanella and Mitchell (1968) in remoulded Illitic specimens which had previously experienced drained thermal cycles. If the slight residual pore pressure build up is ignored, it can be seen that the undrained heating and cooling cycles create an essentially identical hysteresis loop in the v - p' plane. Other studies (e.g. Campanella and Mitchell, 1968) have also reported similar hysteresis loops during undrained thermal cycles.

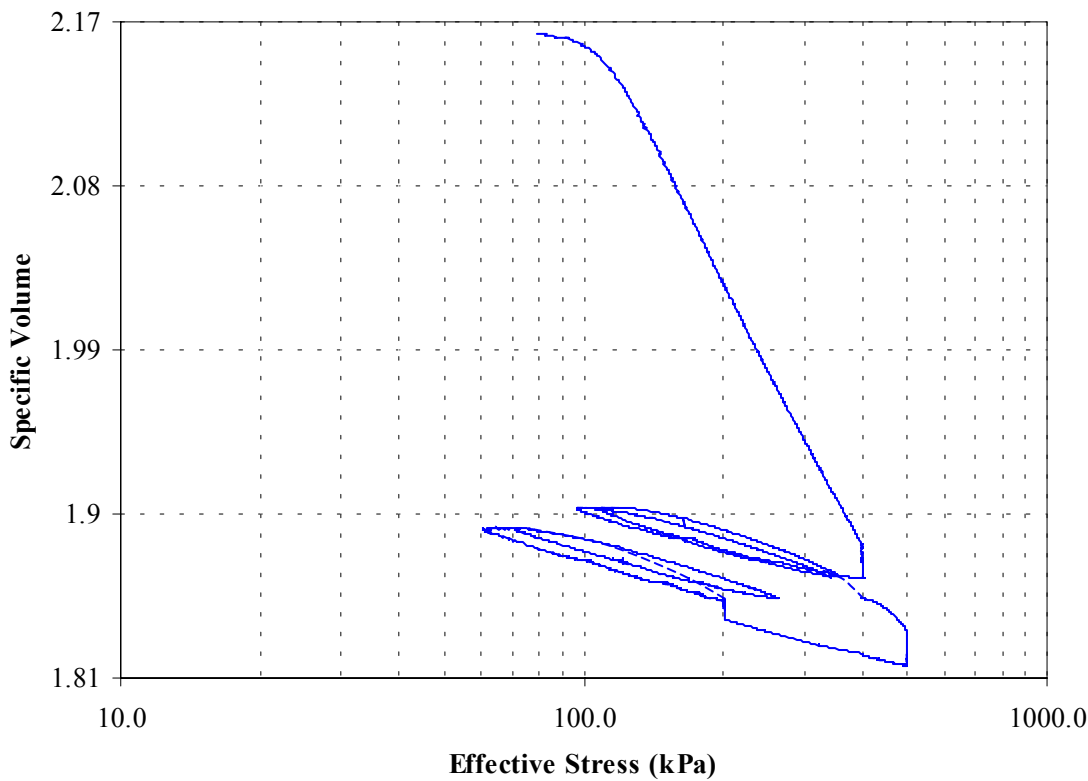


Figure 4.12 Consolidation path in v-p' plane (sample HTUO16)

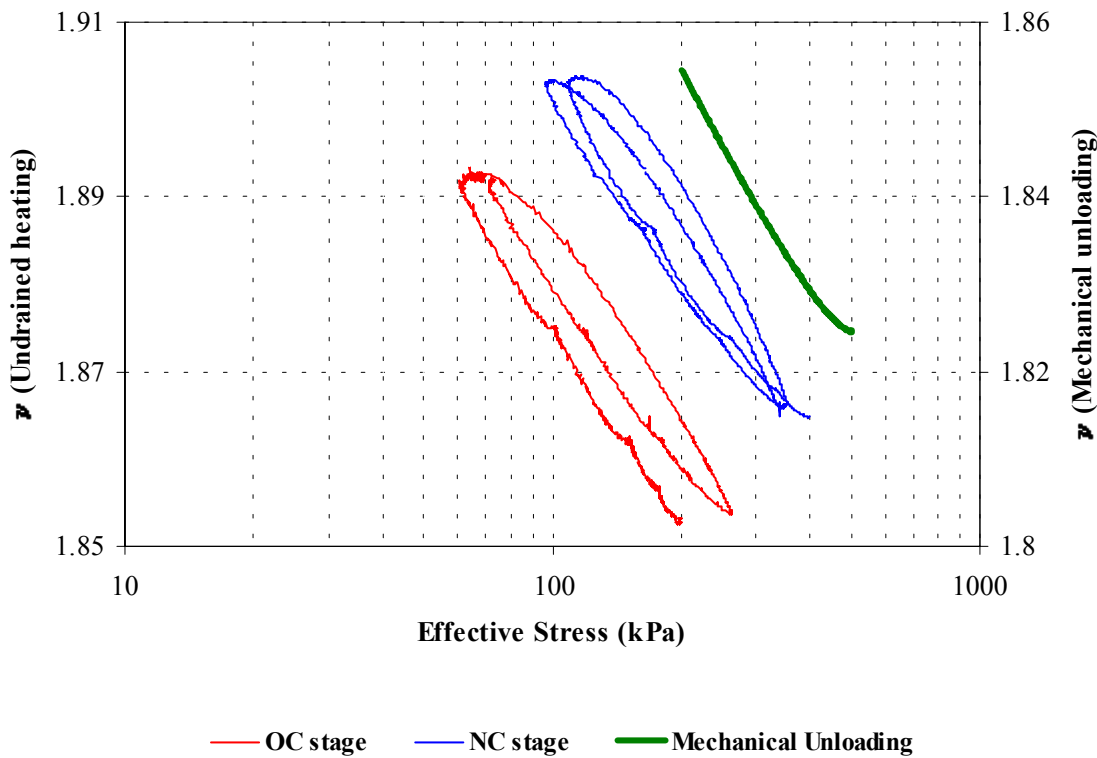


Figure 4.13 Undrained Heating-Cooling cycles of NC and OC stages of sample HTUO16

The other aspect that can be noted from the graph is that the relationships between the specific volume and logarithm of effective stress during undrained heating are not linear. For the purpose of comparison the mechanical unloading curve at room temperature for sample RTUO15 has also been plotted next to the curves for undrained heating. This indicates that the over consolidation of the sample during undrained heating might be treated similarly to that from mechanical unloading. For example heating from 22°C to 75°C in the NC stage reduces the effective stress from 400 kPa to 174 kPa implying an OCR of 2.3 and increases the specific volume from 1.8649 to 1.8863, an overall slope of $9.469 \times 10^{-3}\%$. For the same OCR on the isothermal mechanical unloading curve, there is a reduction in p' from 500 kPa to 217.5 kPa, and an increase from 1.8246 to 1.8513 in specific volume. This corresponds to an overall slope of $9.451 \times 10^{-3}\%$ which is very close to that from undrained heating.

Internal displacement transducers (LVDTs and one PG were available) were used to check if there was any leakage to or from the sample. For example in test, HTUO16, pore pressure changes and the average reading of two LVDTs during the NC part of cyclic undrained heating are drawn in Figure 4.14. The thick and thin curves represent pore pressure and axial displacement respectively. The colour red indicates heating and blue shows cooling. It can be seen that both curves are supporting each other because when the temperature is raised, pore pressure increases and the LVDT readings reduce. The Figure shows that while the volume of the sample is increasing with temperature, the LVDTs are pushed up and show a lower value than before and vice versa. When equilibrium is reached, they both level off, and there is no indication of leakage. Figure 4.15 illustrates the changes in specific volume with changes in temperature during the cyclic undrained heating-cooling of the NC and OC parts of HTUO16. The red and blue lines in Figure 4.15 demonstrate the calculated value of v from corrected volume of sample (considering expansion of pore water and solid particles) and LVDTs (factored) respectively. It should be noted that the volume changes of the sample have been estimated from the measured axial displacement by the LVDTs using $\varepsilon_v = 1.65\varepsilon_a$ (see Figure 4.8). As can be seen in Figure 4.15 the specific volumes determined from both methods have similar shapes and magnitudes, but the strains estimated from the LVDTs are larger than those from the assumed water and solid properties. The proximity gauge was within its working range only in the OC stage when the sample was over consolidated.

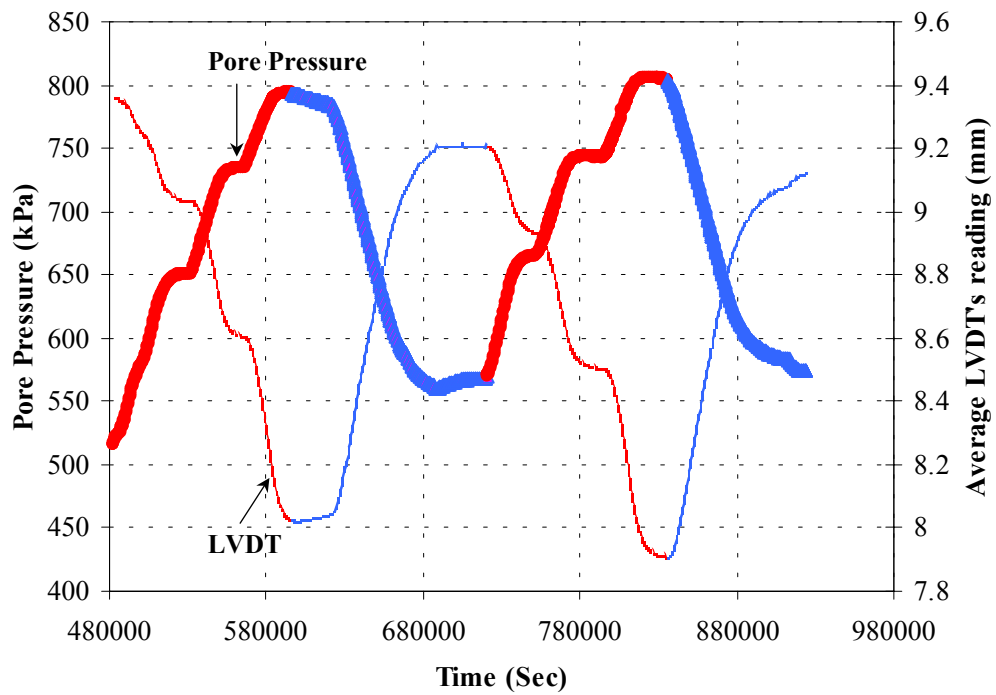
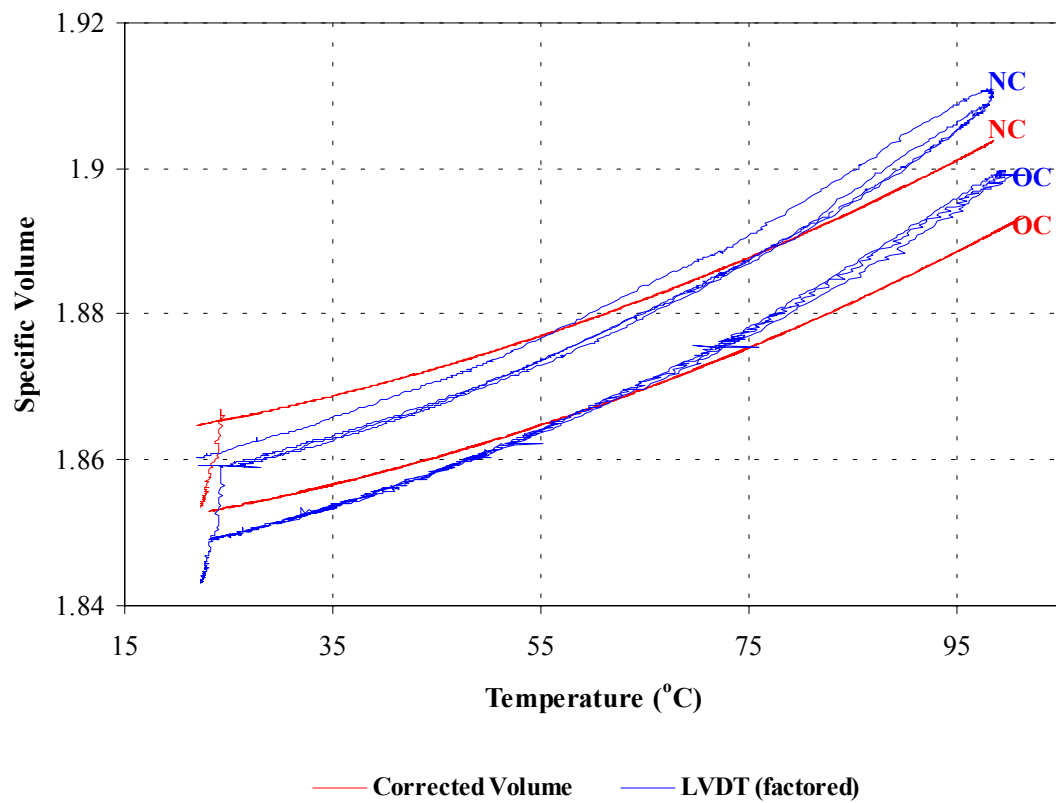


Figure 4.14 Correlation of pore pressure and LVDT's readings

Figure 4.15 Continuous changes in the v during undrained heating and cooling (HTUO16)

By looking at each stage in Figure 4.15, it can be seen that the relationship between v and T is not linear during undrained heating-cooling cycles but it is repeatable. In other words, the volumetric changes of the sample appear to be elastic during undrained changes in temperature. Also the curves in both stages are clearly parallel to each other indicating that undrained thermal volume changes are independent of effective stress level and OCR. Figure 4.16 presents the changes of pore pressure (PP) and axial displacement (AD) with temperature. Similar to Figure 4.12, this graph also shows the residual pore pressure build up in the first cycle of heating-cooling while the displacement curves show a clear repetitive and elastic response to undrained changes in temperature. As mentioned earlier the build up of residual pore pressure appears to be reducing in the subsequent cycles leading to a steady hysteresis loop.

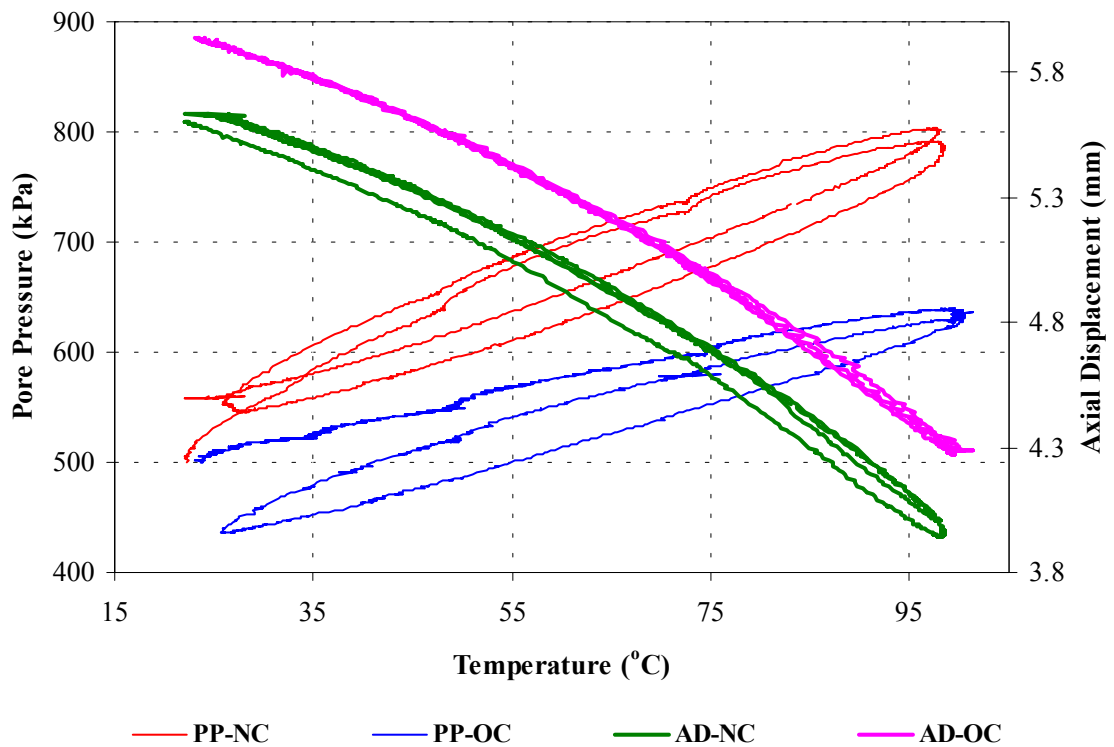


Figure 4.16 Changes in pore pressure (PP) and axial displacement (AD) during undrained thermal cycles (HTUO16)

The changes in radial and axial displacements with temperature in the OC state of sample HTUO16 are shown in Figure 4.17.

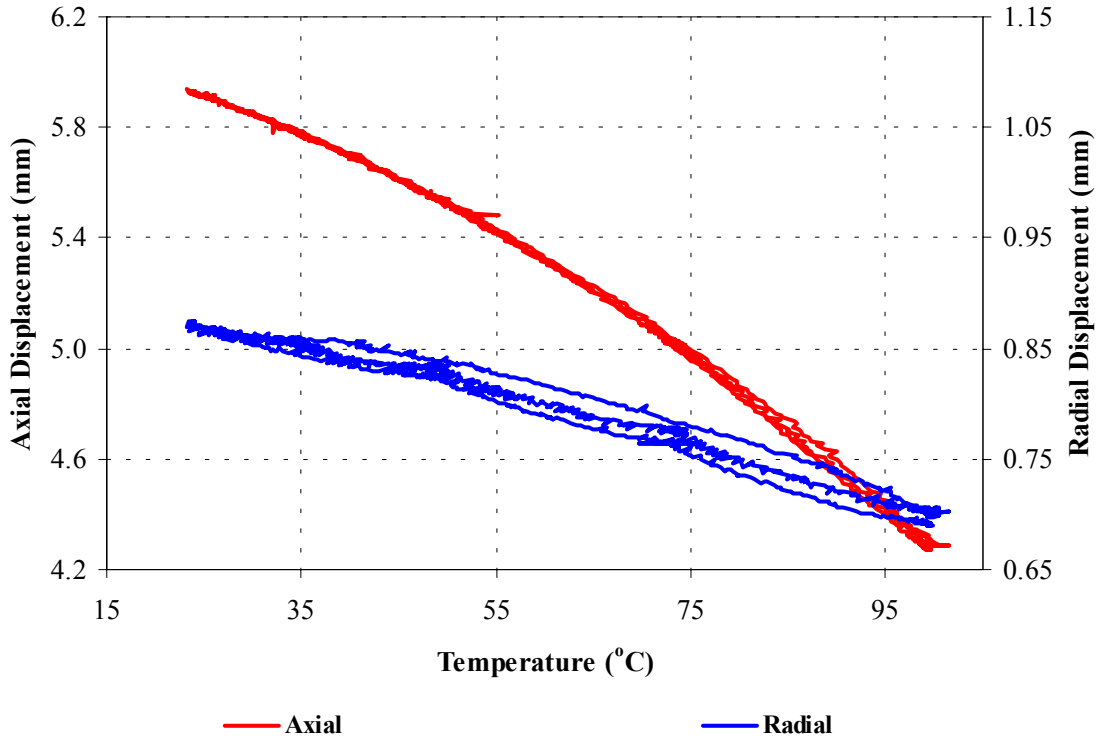


Figure 4.17 Variations of axial and radial displacements with temperature in the OC stage

Neither the hysteresis loop nor residual strains are evident in the axial and radial displacement curves indicating that the volume of sample is changing elastically with temperature. It was mentioned in chapter 3 that during calibration of the volume changes in the drainage lines hysteresis loops similar to those shown in Figures 4.13 and 4.16 were observed. Considering the fact that the rates of heating and cooling were very slow (less than 0.09 °C/min in these tests), the reported lagging might be related to the physical properties of the pore water such as its heat capacity and thermal conductivity, which are known to be dependant on temperature. However, the mechanism is not clear at this stage. The residual pore pressure might be the result of slight physico-chemical changes in the clay and non-uniform deformation of the sample.

The specific volumes at the end of isotropic thermo-mechanical consolidation of all M44 clay samples are plotted versus mean effective stress, p' , in Figure 4.18. The relationship between v and natural logarithm of effective stress is linear and given by:

$$v = N - \lambda \ln p' \quad (4.21)$$

Some of the data points, which were believed to be faulty and affected by some imperfections during the tests, have been removed. It can be noticed that the drawn isotropic normal consolidation lines, INCL, at different temperatures are nearly parallel. They have the same slope, λ , but have different initial specific volumes at $p' = 1$ kPa, N .

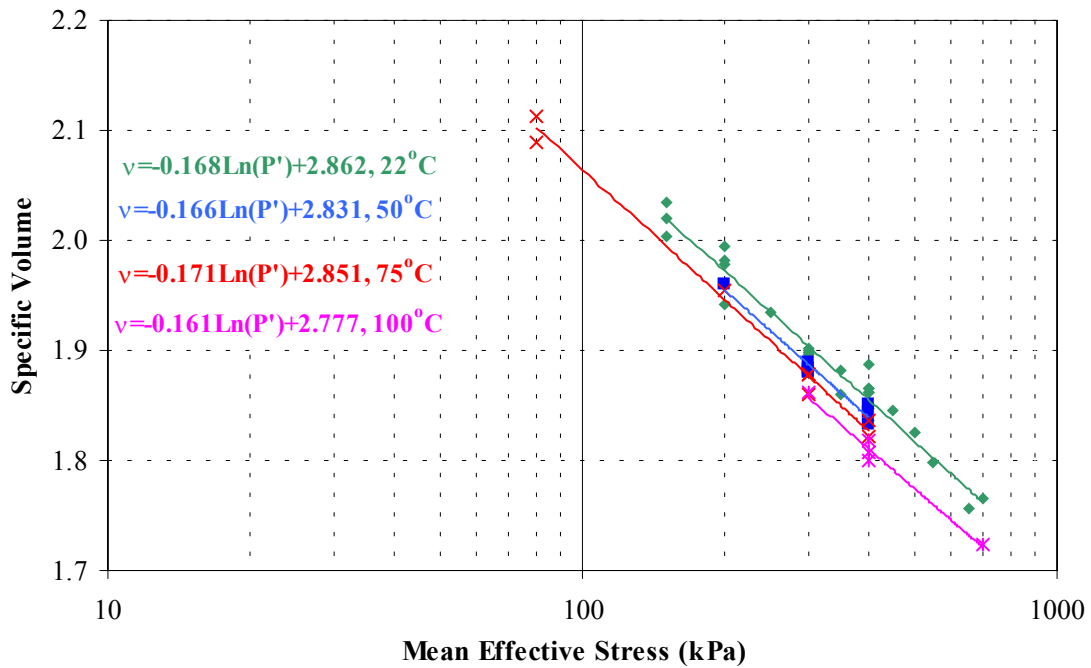


Figure 4.18 Isotropic normal consolidation lines at different temperature

This is in agreement with the findings of other researchers such as Campanella and Mitchell (1968) and Graham et al (2001). The equations for each INCL are written on the chart with the same colour as the line itself. The green, blue, red and magenta colours represent the temperatures of 22°C, 50°C, 75°C and 100°C respectively. It is clear from the graph that the amount of thermal consolidation of NC samples is independent of the effective stress level. The variations in the INCLs with temperature are further discussed in section 4.2.2.5.

4.2.2.2 Secondary consolidation

The coefficient of secondary consolidation, C_{α} , of M44 clay was determined using equation 2.9. During consolidation of sample RTDN6 the effective stress was increased

in one step from 80 kPa to 200 kPa and the sample was left to consolidate for 122 hours (about 5 days). The variation of specific volume with logarithm of time for the last 49 hours of consolidation are shown in Figure 4.19.

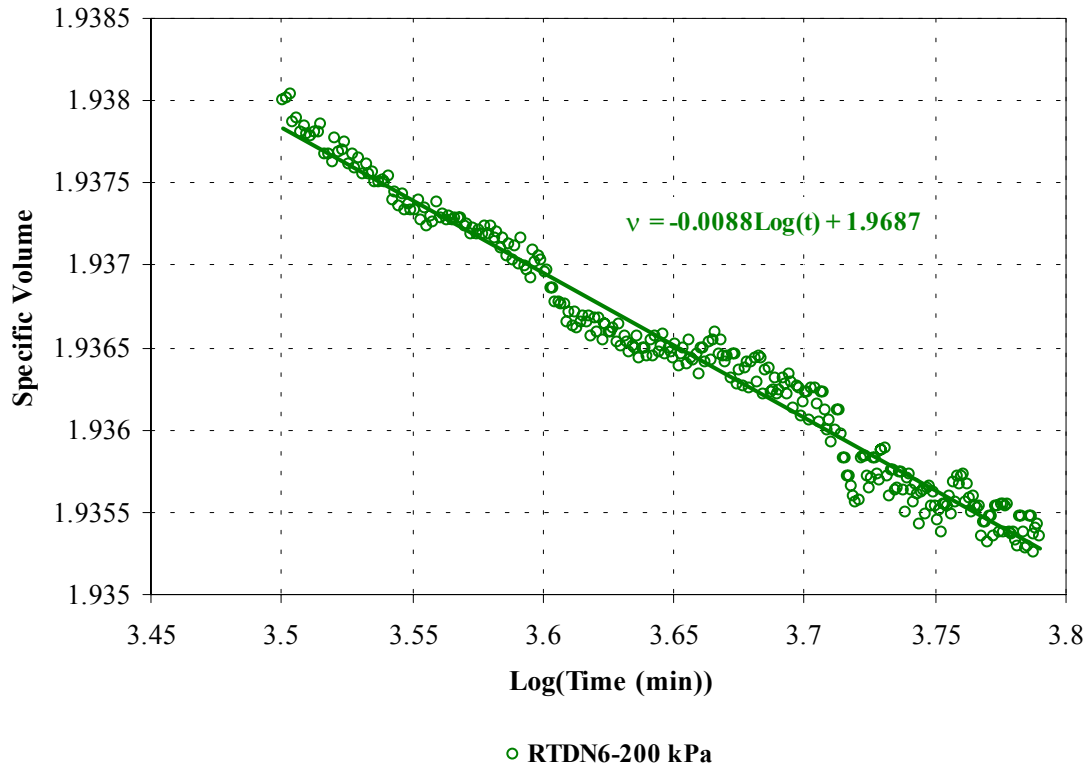


Figure 4.19 Variations of specific volume with logarithm of time at end of stepwise consolidation

As can be seen the specific volume is linearly changing with the logarithm of time and the slope of the best-fit line gives the coefficient of creep at room temperature to be $C_\alpha = 0.009$. C_α values were also determined from tests with incremental consolidation (rate of increase in effective stress = 0.2 kPa/min) at different temperatures when the stress was held constant. Figure 4.20 demonstrates the variation in the specific volume with logarithm of time when initial consolidation was finished. Colours green, red and magenta represent tests at 22°C, 75°C and 100°C respectively. It is clear from the graph that C_α does not significantly change with temperature and its average value is 0.0116. The compression index, C_c , was found to be 0.378 for M44 clay and consequently the ratio of C_α/C_c would be 0.03 which is lower than for most clays. Therefore the effects of creep are expected to be small during thermo-mechanical consolidation. Nevertheless

attempts have been made to minimise any creep effects by allowing similar amounts of elapsed time after completion of initial consolidation.

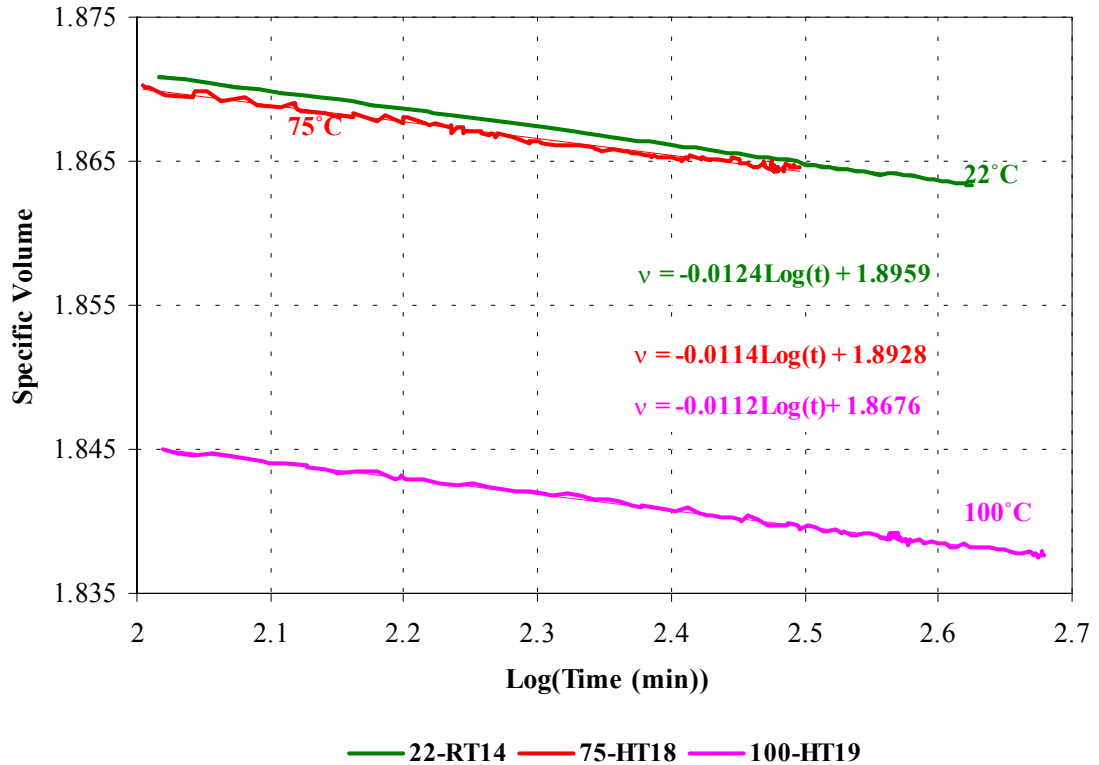


Figure 4.20 Variations of specific volume with logarithm of time at the end of incremental consolidation

4.2.2.3 Cubical thermal expansion of M44 clay particles

It has been shown earlier that the undrained thermal volumetric changes are purely elastic, but not linear. The non-linearity may be expected because the volumetric coefficient of thermal expansion of water is a function of temperature (see Figure 4.3). In contrast, it has been claimed by some researchers (e.g. Lingnau et al 1995, Tanaka et al 1996, Graham et al 2001) that the undrained coefficient of thermal expansion of soil, $\alpha_u = \varepsilon_v / \Delta T$, is constant indicating a linear relationship between undrained volumetric strain and temperature. Figure 4.21 shows the changes in α_u determined from the LVDTs (factored) with temperature for sample HTUO16. Thermal volume expansion has been considered to be negative in sign.

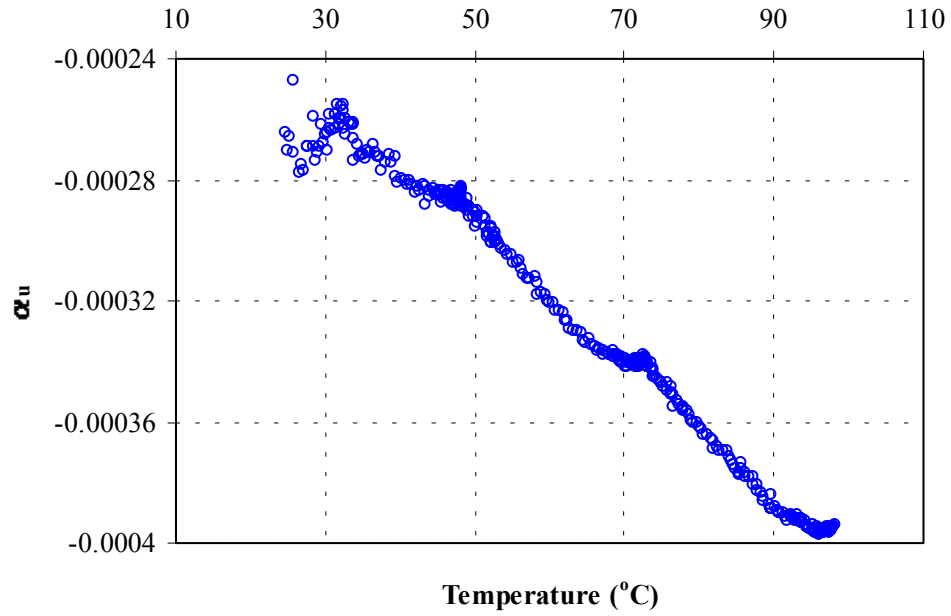


Figure 4.21 Variations of α_u with changes in temperature for M44 clay

As can be seen in the graph, α_u is not a constant and changes almost linearly with temperature. It increases from $(-)0.00025$ at 22°C to $(-)0.00039$ at 100°C .

It has been assumed that the elastic volume changes during undrained heating are the direct result of thermal expansion of water and solid particles. Therefore the value of α_s , the cubical coefficient of thermal expansion of solid particles, can be calculated directly from the displacements measured by the internal transducers mainly LVDTs using the following equations:

$$\Delta V = \alpha_w V_w \Delta T + \alpha_s V_s \Delta T + \Delta V_w(\text{system}) \quad (4.22)$$

Rearranging:
$$\varepsilon_v = \frac{v-1}{v} \alpha_w \Delta T + \frac{1}{v} \alpha_s \Delta T + \varepsilon_v(\text{system}) \quad (4.23)$$

Where $\Delta V_w(\text{system})$ and $\varepsilon_v(\text{system})$ are thermal volume changes and volumetric strain in the sample due to changes in the volume of water in the porous disc and drainage tube. Combining 4.16, 4.23 and integrating over the range of temperature change, 4.23 becomes:

$$\varepsilon_v = \frac{v-1}{v} [EXP\{3.45 \times 10^{-6} (T^2 - T_0^2) + 9.79 \times 10^{-5} (T - T_0)\} - 1] + \frac{1}{v} \alpha_s (T - T_0) + \varepsilon_v(\text{system}) \quad (4.24)$$

It has been considered that the thermal volumetric strain is given by:

$$\varepsilon_v = A\varepsilon_a \quad (4.25)$$

The values of axial strain were calculated from direct measurement by the LVDTs. Factor A was determined from table 4.1 and Figure 4.8 based on the state of consolidation. Equation 4.24 is true if the water in the pores behave as free water (bulk water).

As mentioned earlier the volumetric strain during drained reheating-cooling cycles (see Figure 4.7) can be considered elastic, and if it is assumed to be a direct result of changes in the volume of solid particles, α_s can be calculated from the following equation:

$$\alpha_s = \frac{\Delta V_{\text{int}}}{V_s \Delta T} \quad (4.26)$$

ΔV_{int} is the sample volume change measured by the internal instrumentation or based on the LVDTs allowing for the non-uniform deformation.

The results during undrained and drained heating are summarized in Table 4.2. α_s (undrained) has been determined from four undrained heating-cooling cycles applied to sample HTUO16 and has been averaged for each temperature category. α_s (drained) is the average of two values (3.2×10^{-5} and $1.2 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$), calculated from drained reheating-cooling responses of sample HTUO17 at NC and OC stages. The value of α_s (drained) was assumed to be constant for all temperatures.

Table 4.2 Average values of α_s calculated from heating tests on M44 clay

Temperature $^\circ\text{C}$	α_s (undrained) $^\circ\text{C}^{-1}$	α_s (drained) $^\circ\text{C}^{-1}$
22-50	0.000079	0.000022
22-75	0.000098	0.000022
75-100	0.00019	0.000022

The α_s of $3.5 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ has been recommended by Campanella and Mitchell (1968) for similar substances to Kaolinite and Illite. It has been shown by Derjaguin et al (1986) that the thermal behaviour of water in the pores and the free water are very close at temperatures higher than 70°C . As can be seen in the table for temperatures above 75°C the average values of 1.9×10^{-4} and $2.2 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ for α_s have been calculated from undrained and drained methods respectively. The average α_s calculated from drained

heating is very close to the reported value. This indicates that the thermal volume changes of solid particles are essentially responsible for volumetric changes of the sample during drained reheating-cooling cycles and the assumption of elasticity was appropriate. The average value of α_s determined from undrained heating is about 5.4 times higher than the reported value. As undrained thermally induced volumetric strains ($\sim 3.5\%$ from 22°C to 100°C) are relatively bigger than those from drained reheating-cooling cycles, a greater error is expected due to the assumption of $\varepsilon_v = A\varepsilon_a$. Although it was shown earlier that the factor A changes with the state of consolidation A was assumed to be 1.65 because of the thermal overconsolidation during undrained heating, which is similar to the mechanical overconsolidation shown in Figure 4.8 for which $A = 1.65$ was measured. In the absence of a proper radial displacement measurement the calculation of α_s from undrained heating and cooling cycles is expected to be overestimated due to the relatively large volumetric strain and the uncertain variation of factor A . A sensitivity analysis revealed that the corrected specific volume and volumetric strain to allow for temperature changes would not be significantly affected with the error in α_s , and it was decided to not repeat all the calculations. The comparison with Kaolin C1C is made later in this chapter.

4.2.2.4 Shearing characteristics of M44 Illitic clay

The results from the isothermal drained and undrained triaxial shearing tests on M44 clay are reported in Table 4.3. Each row shows a specimen number, the temperature at which the shearing was carried out, the mean effective stress at the end of consolidation (p'_c), the effective deviator and mean effective stress at failure (q_f , p'_f), the specific volume at failure (v_f , at that temperature), the normalized shear modulus at small strain (G/p'_c) and finally the normalized secant modulus at fifty percent of maximum deviator stress (G_{50}/p'_c). The maximum deviator stress has always been considered as the failure point. Failure in most cases occurred with barrelling and occasionally with the development of shear planes. The letters in the sample number are in order from left to right: temperature status (RT for room and HT for high temperature), drainage condition (D or U), consolidation status (N for normally and O for over consolidated), and the final characters are the test number.

Table 4.3 Results from undrained and drained triaxial shear tests on M44 clay

Sample No.	Temperature °C	P'_c (kPa)	q_f (kPa)	P'_f (kPa)	v_f	G/P'_c	G_{50}/P'_c
RTUN1	22	550	242.2	299.2	1.7985	67.9	28.1
RTUN2	22	350	163.8	188.2	1.8607	51.5	28.5
RTUN3	22	150	81.0	84.6	2.0039	48.1	42.2
RTUO4	22	50	86.2	85.2	1.8011	53.4	21.9
RTUN5	22	150	72.9	76.8	2.0193	53.0	40.3
RTDN6	22	250	254.5	331.8	1.7967	50.6	4.7
RTDN7	22	450	423.8	591.3	1.7121	15.0	4.3
RTUO8	22	50	111.1	120.1	1.8665	84.6	23.9
RTUN9	22	300	137.5	169.8	1.9371	129.7	49.2
RTDN10	22	400	326.2	507.7	1.7579	147.9	6.1
RTUN11	22	400	183.7	221.5	1.8507	93.8	36.8
RTUN12	22	200	88.5	104.5	1.9810	122.1	42.0
RTUN13	22	400	202.9	219.6	1.8665		33.7
RTUN14	22	400	195.1	218.7	1.8627	104.5	22.6
RTUO15	22	200	168.7	195.3	1.8586	142.1	32.7
HTUN2	50	300	154.4	173.2	1.8839	38.7	24.6
HTUN3	50	400	172.5	230.3	1.8428	32.4	22.0
HTUN4	50	300	149.2	173.7	1.8796	25.8	17.5
HTDN5	75	400	312.1	503.8	1.7574	16.4	4.4
HTDN6	75	200	198.5	264.5	1.8337	36.4	6.9
HTUN7	75	300	128.3	161.2	1.8787	39.3	26.7
HTUN8	100	200	104.8	124.8	1.9061	35.3	21.3
HTUN9	100	400	206.0	242.8	1.8005	207.3	28.7
HTDN11	100	300	296.0	398.2	1.7653	50.2	5.1
HTUN12	100	400	162.1	232.9	1.8081	26.2	15.1
HTUN13	50	200.0	96.8	118.6	1.9604	123.0	36.6
HTUO14	100	700-100	104.0	123.1	1.8600	262.1	32.6
HTUO15	100	700-100	122.0	148.1	1.8246	46.0	27.7
HTUO16	100	500-200	130.6	154.1	1.8546	155.4	36.0
HTUO17	100	500-200	137.1	172.5	1.8382	151.8	43.5
HTUN18	75	400	179.0	208.1	1.8641	60.1	13.8
HTUN19	100	400	159.3	201.6	1.8376	28.9	14.0
HTDN20	75	400	383.8	529.2	1.7596	44.3	4.7

Typical undrained stress-strain curves of normally consolidated samples at different temperatures are shown in Figure 4.22. The green, blue, red and magenta colours are indicating temperatures of 22°C, 50°C, 75°C and 100°C respectively. In the graph's key, the number before comma is the test number, and this is followed by p'_c , the effective consolidation stress. The letter H before the stress indicates that heating occurred before mechanical consolidation, and if H is after the number heating occurred after

mechanical consolidation. The deviator stress has been normalized with p'_c , the effective stress at the end of consolidation.

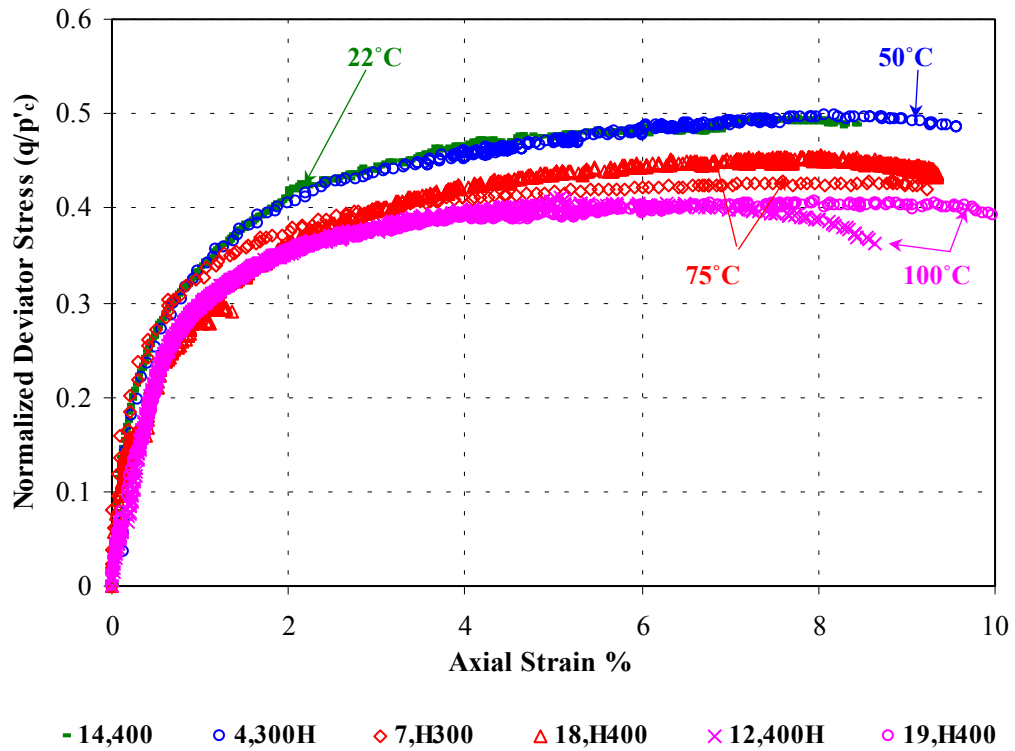


Figure 4.22 Stress-Strain response of normally consolidated M44 clay to undrained shearing

Although there are some slight differences between the curves for the same temperature, there is a clear pattern showing a reduction in undrained shear strength and stiffness with an increase in temperature. It appears that elevated temperatures do not significantly affect the ductility of this soil during undrained shear. The samples HTUN12 and HTUN19 tested at 100°C had different consolidation histories. The former was mechanically consolidated before raising the temperature whereas the latter was heated at low effective stress before being mechanically consolidated. It is shown in Figure 4.22 that they both have practically identical responses suggesting that the order of thermal and mechanical consolidation has little influence at least for NC samples. Figure 4.23 illustrates the variation of normalized pore pressure with axial strain during undrained shear at temperatures between 22°C and 100°C.

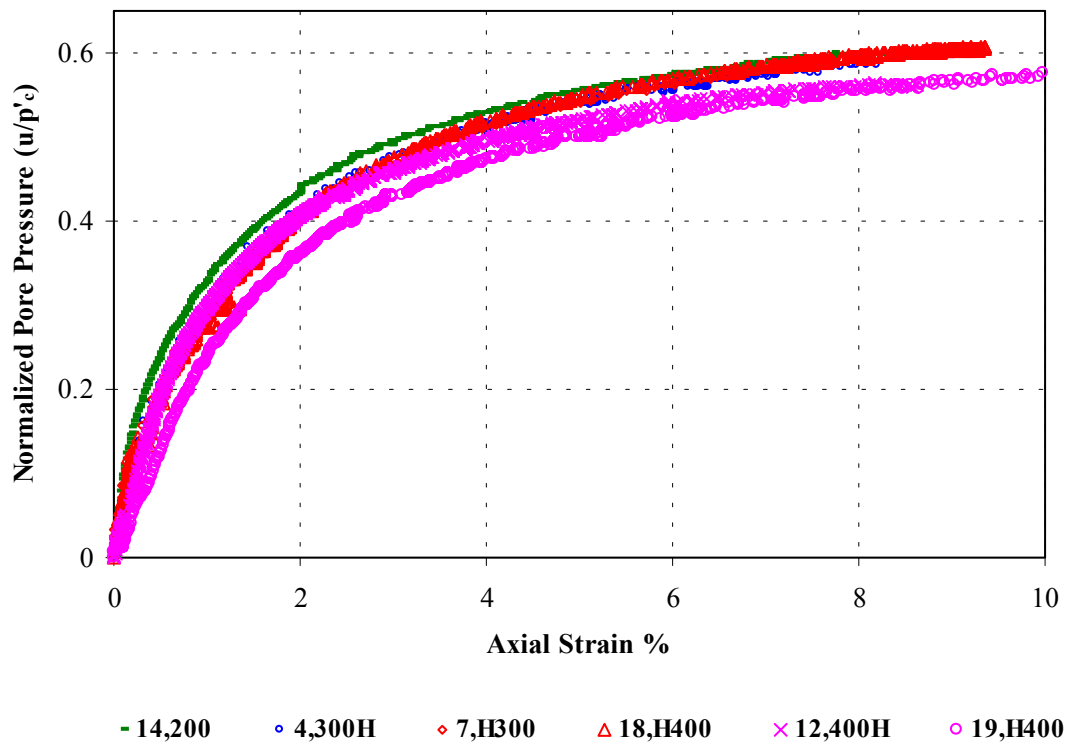


Figure 4.23 Pore pressure changes during undrained shear test on M44 clay

There is a slight reduction in the maximum pore pressure as the temperature reaches 100°C but there is no obvious trend with temperature. Typical relationships between normalized deviator stress and normalized mean effective stress for normally consolidated samples are demonstrated in Figure 4.24. The reduction in strength is also clear in this graph. The small variation of p'/p'_c from unity at the start of shearing is a consequence of creep and the longer elapsed time between closing the drainage line and load application in those tests. Figure 4.24 shows that not only does the peak deviator stress reduce, but also there is a trend for the mobilised friction angle to reduce with temperature. Only typical data are presented here for clarity. The results from all the undrained tests are reported in appendix 4.C.

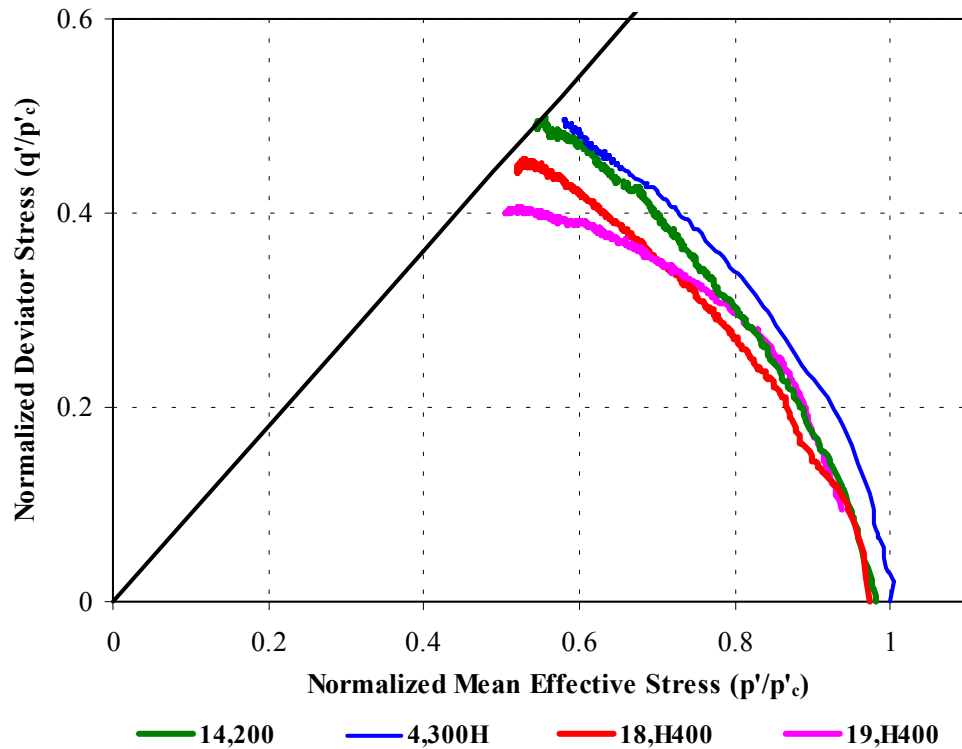


Figure 4.24 Stress path at different temperatures during undrained triaxial test on M44 samples

Figure 4.25 presents the stress-strain paths of overconsolidated samples during undrained shear tests at room and elevated temperatures. In the legend, green shows tests at room temperature and magenta represent tests at 100°C, the number before the comma is the test number, UHC and DHC refer to undrained and drained heating cycles, the letter H indicates the stage at which heating occurred. For example, 16,UHC500-200UHC refers to sample no. HTUO16 that has undergone cycles of undrained heating-cooling (at initial $p' = 400$ kPa) before drainage was allowed, then consolidation to a maximum p'_c of 500 kPa, and then unloading to 200 kPa. Subsequently it experienced a few undrained heating-cooling cycles before drainage was permitted and it finally was sheared under undrained conditions. Samples HTUO16 and HTUO17 both have the same over consolidation ratio ($OCR = 2.5$) but have different consolidation histories similar to paths G and H respectively (see Figure 4.2). Specimen RTUO15 was mechanically consolidated to p'_c of 500 kPa and then unloaded to 200 kPa ($OCR = 2.5$) all at room temperature. This sample presents higher normalized undrained shear strength than samples HTUO16 and HTUO17 but it demonstrates similar stiffness at low strains. The undrained (HTUO16) and drained

(HTUO17) heating-cooling cycles, followed by drainage, appear to have similar effects on stress-strain response of specimens HTUO16 and HTUO17.

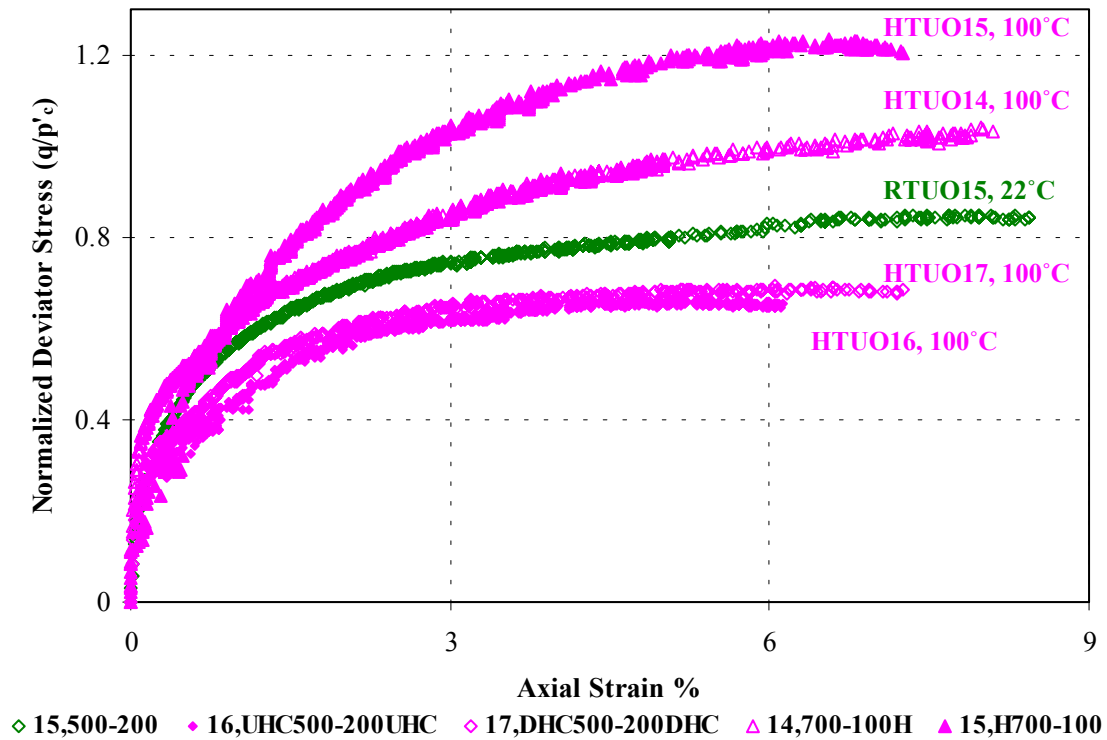


Figure 4.25 Stress-Strain paths for over consolidated samples of M44 clay

The samples HTUO14 and HTUO15 have higher OCR (7) and they have followed consolidation paths E and F in Figure 4.2, respectively. In the former, mechanical consolidation and over consolidation were carried out prior to thermal consolidation while in the latter the sequences were reversed. The results from these two tests on highly overconsolidated samples show that if isotropic mechanical consolidation and over consolidation happen after thermal consolidation a higher undrained shear strength occurs than for the reverse order. This type of sensitivity to thermo-mechanical consolidation history was not evident for NC and lightly OC samples. The difference between the curves is greater than that due to experimental differences in otherwise similar results. A maximum normalized value of $q/p'_c = 2.24$ was estimated for an overconsolidated sample (OCR = 7) at room temperature using the critical state line determined from the room temperature tests. This value is well above the observed values of q/p'_c (max) at 100°C indicating a possible reduction in peak undrained shear

strength as is also observed for $OCR = 2.5$. Further experimental data would be required to confirm this observation, as highly OC samples tend to fail before reaching a critical state.

The normalized pore pressure changes with axial strain are illustrated in Figure 4.26.

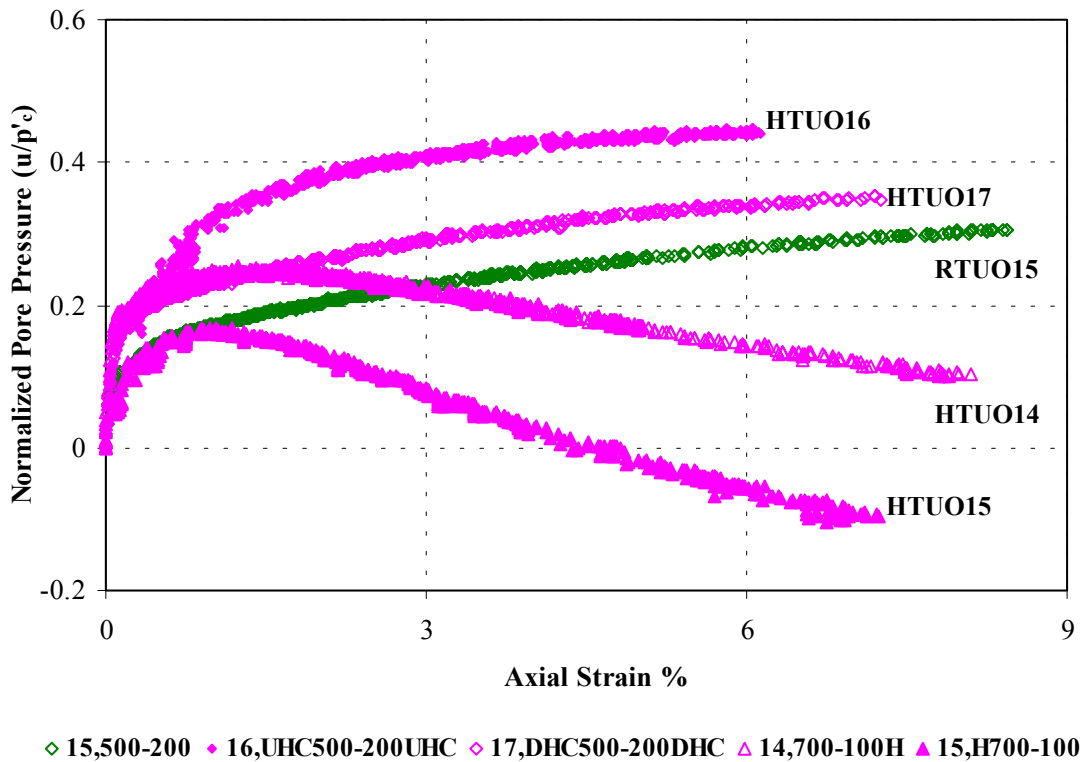


Figure 4.26 Pore pressure development of overconsolidated samples during undrained shear test

The pore pressure was normalized by p'_c . Pore pressure development in samples RTUO15, HTUO16 and HTUO17 ($OCR = 2.5$) are similar but have different magnitudes. Sample RTUO15 develops the lowest pore pressure during shearing followed by HTUO17 and HTUO16. Sample HTUO14 reaches higher pore pressure at failure compared to HTUO15 and consequently presents lower shear strength.

The effective stress paths of overconsolidated samples are drawn with the normally consolidated samples in the normalized $q: p'$ plane in Figure 4.27. The black line is the strength envelope for samples sheared at room temperature. As can be seen the samples at elevated temperature did not reach this line and have higher distances to this envelope than the room temperature samples.

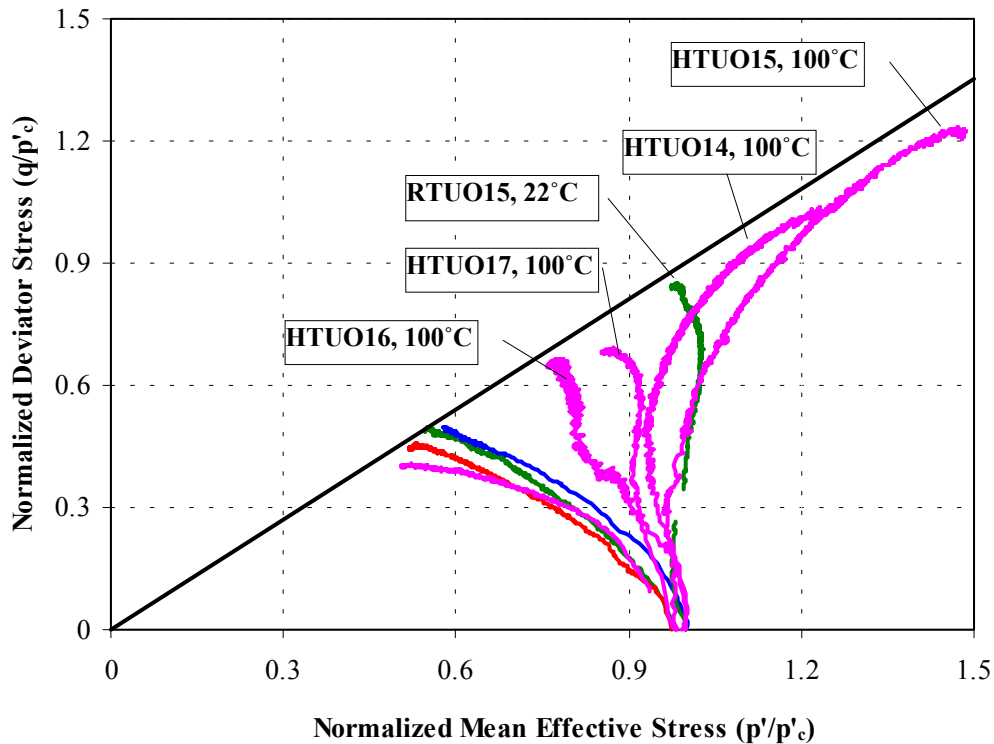


Figure 4.27 Effective stress paths of M44 samples

Typical stress-strain paths from drained triaxial shear tests on NC M44 clay are demonstrated in Figure 4.28. Figure 4.29 displays the associated changes in volumetric strain with changes in axial strain. The green, red and magenta colours relate to temperatures of 22°C, 75°C and 100°C respectively. There is a slight trend for higher stress and lower volume change with increasing temperature. The two tests at 75°C show responses coinciding with 100°C and 22°C responses but not consistently. This may be a consequence of the different orders of mechanical and thermal consolidation of the two samples. The stiffness also seems to remain unchanged by temperature fluctuations.

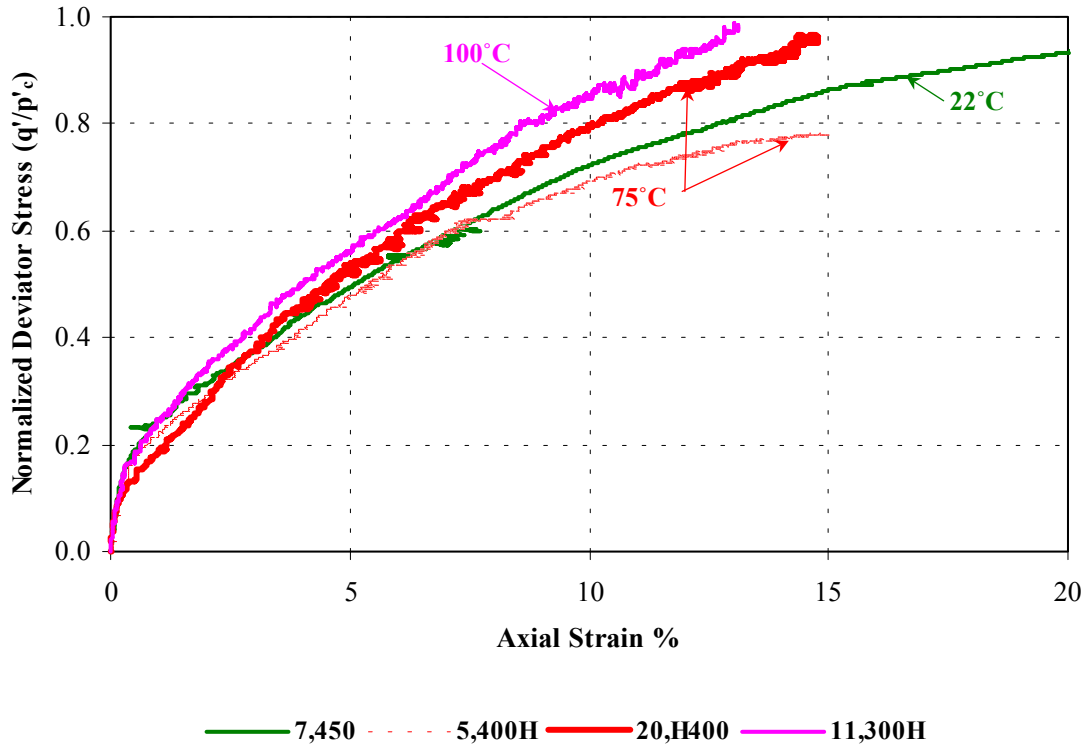


Figure 4.28 Drained Stress-Strain response of normally consolidated samples

Figures 4.28 and 4.29 show that the ductility of the samples during drained tests reduces slightly at higher temperatures. The reduction of ductility at elevated temperature has been also reported by Chiu (1996) during drained triaxial tests on NC samples of Kaolin C1C.

The value of Poisson's ratio was determined from the slope of ε_v - ε_a curve in Figure 4.29 at the beginning of shearing where the volume change curve might be considered as the elastic response of the soil to the stress change (Wood 1990). The following relationship was used to calculate Poisson's ratio:

$$\mu = \frac{1}{2} \left(1 - \frac{\Delta \varepsilon_v}{\Delta \varepsilon_a} \right) \quad (4.27)$$

The average value of 0.25 was determined at all temperatures, as all ε_v - ε_a curves seem to have very similar slopes at the beginning of shearing. It should be noted that the volumetric strains during drained tests have always been determined using the volume changes measured by the GDS controller.

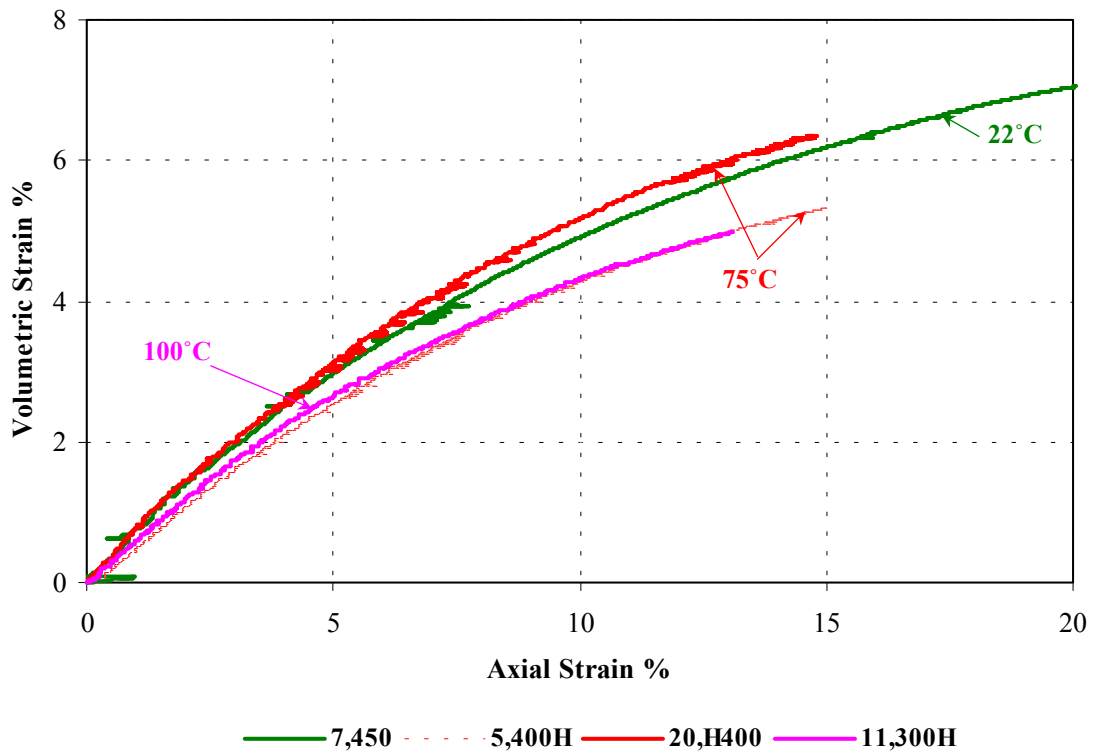


Figure 4.29 Changes in the volumetric strain during drained shear tests on NC samples of M44 clay

In order to show the effects of temperature on the stiffness of M44 clay the calculated normalized secant modulus, G/p'_c , from different tests is plotted versus shear strain in Figures 4.30, 4.31 and 4.32. In all three Figures green, blue, red and magenta represent temperatures of 22°C, 50°C, 75°C and 100°C respectively. Also all graphs only use the results of tests in which the internal displacement transducers were implemented. Figure 4.30 illustrates the data from the undrained triaxial shear tests on normally consolidated samples of M44 clay. It is observed that for a given temperature the ratio of G/p'_c is nearly constant for shear strains of less than 0.01% and it increases with a reduction in temperature. In the range of 22°C to 50°C, the normalized secant modulus is approximately between 120 and 150. This value is reduced to 85 and 35 at 75°C and 100°C respectively. Also it can be noticed from the graph that the order of thermal and mechanical consolidation, as shown for HTUN12 and HTUN19, is not important.

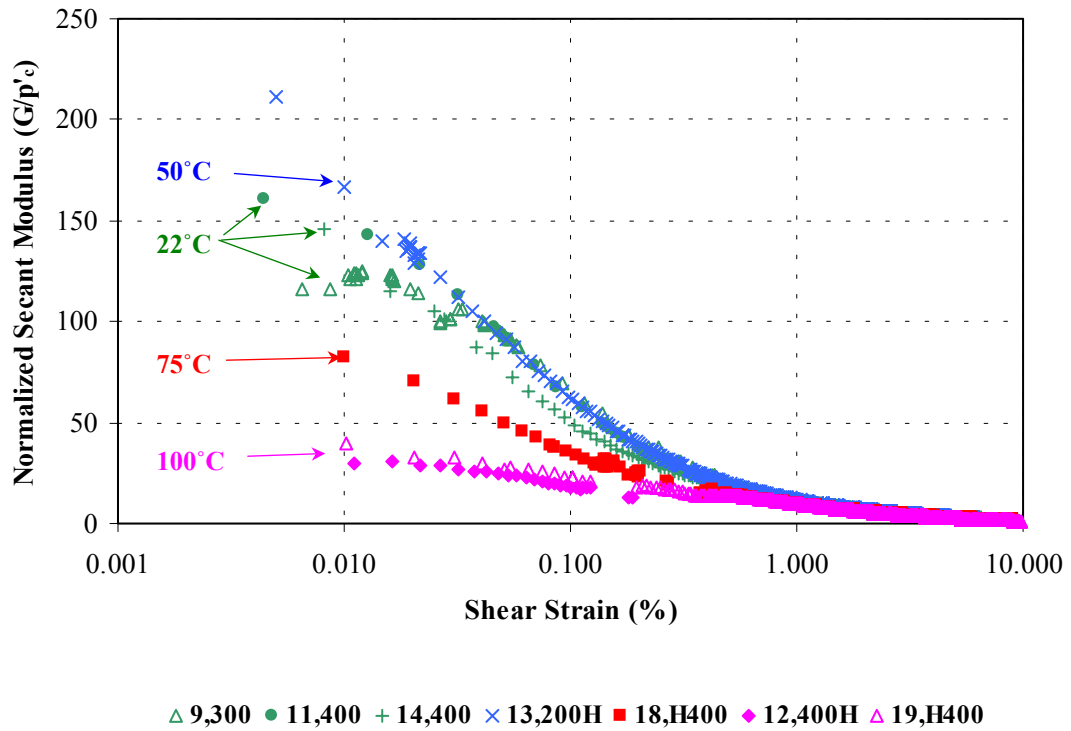
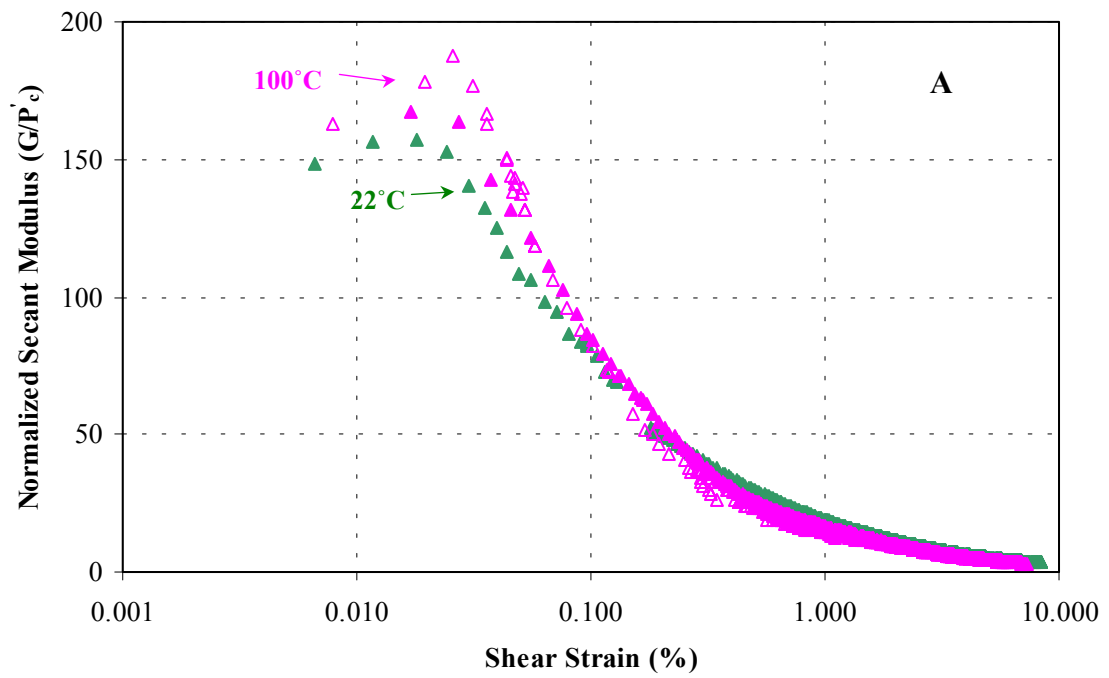


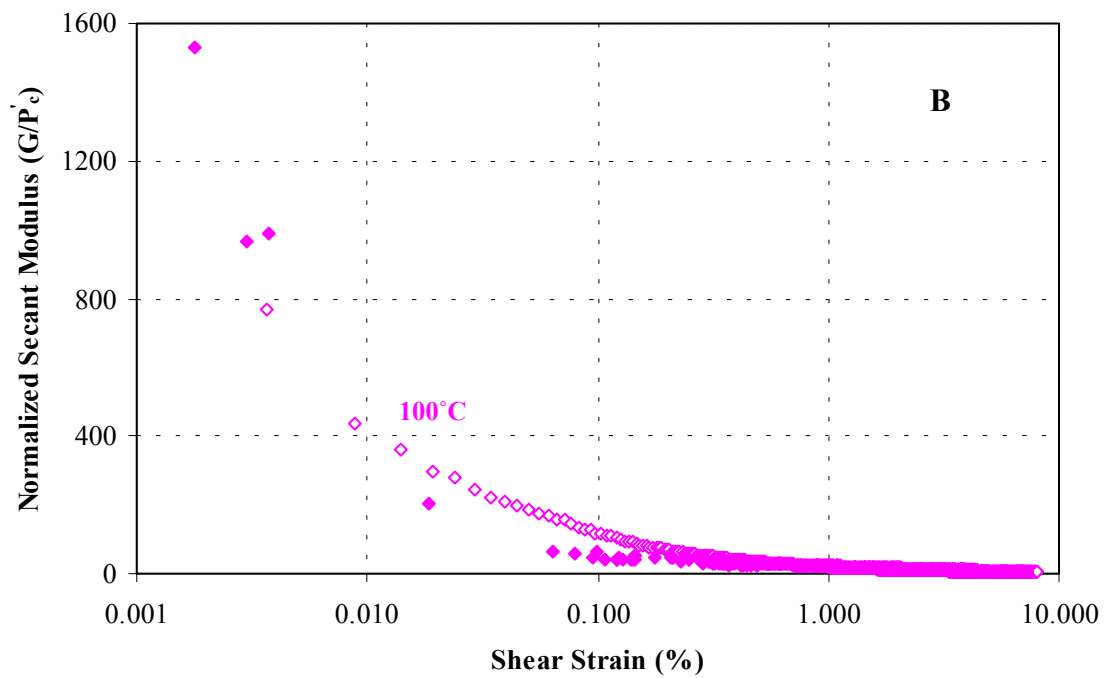
Figure 4.30 Variations of normalized effective shear modulus with temperature during undrained tests

Figures 4.31A and 4.31B are drawn from undrained shear test data on overconsolidated samples. Tests HTUO16, HTUO17, and RTUO15 are pointing to a value of around 160 ± 10 for G/p'_c at 0.01 % shear strain compared to 140 for NC samples at room temperature and it seems to be independent from temperature changes and consolidation history for lightly OC ($OCR = 2.5$) samples. At $OCR = 7$ (Figure 4.31B), HTUO14 and HTUO15 present higher G/p'_c values because of the higher overconsolidation ratio. The threshold shear strain below which the samples behave elastically could not be detected. The effects of thermal consolidation history on stiffness do not seem to be significant as the two tests show similar responses.

Figure 4.32 is based on the results from 3 drained shear tests on NC samples. The chart demonstrates that the normalized shear modulus at 22°C is 150 when shearing starts (similar to the undrained tests), and this value reduces to around 60 at 75°C and 100°C. The pattern of reduction with temperature in the small strain stiffness of clay during drained tests on NC samples agrees with the results from the undrained tests.



▲ RT15,500-200 ▲ 16,UHC500-200UHC ▲ 17,DHC500-200DHC



◆ 14,700-100H ◆ 15,H700-100

Figure 4.31 Changes in the undrained stiffness of OC samples with temperatures for [A] OCR = 2.5, [B] OCR = 7

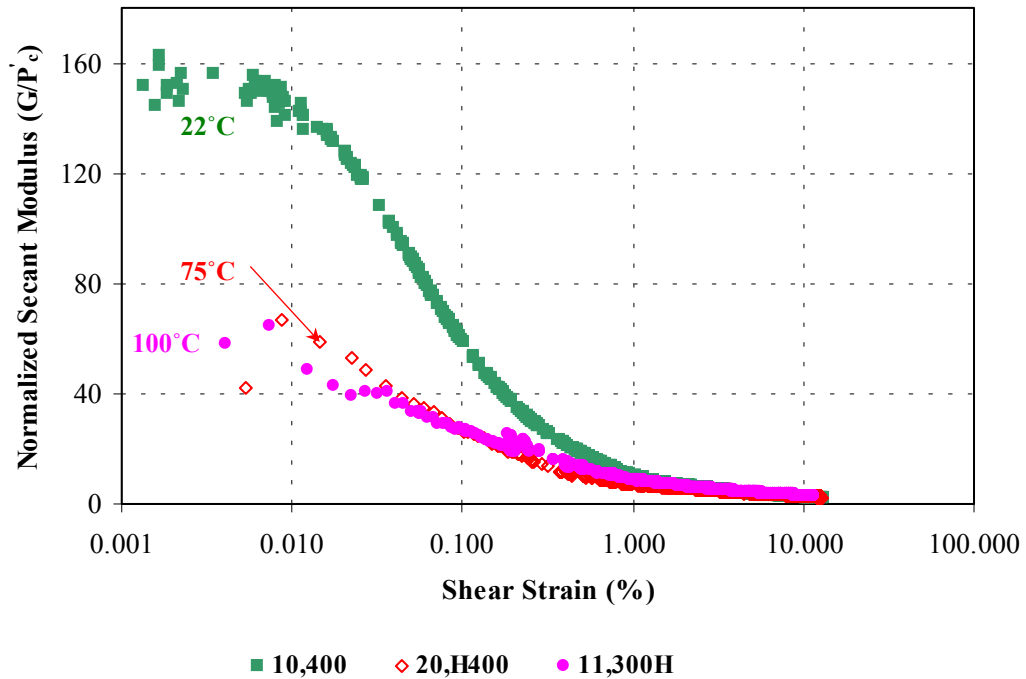
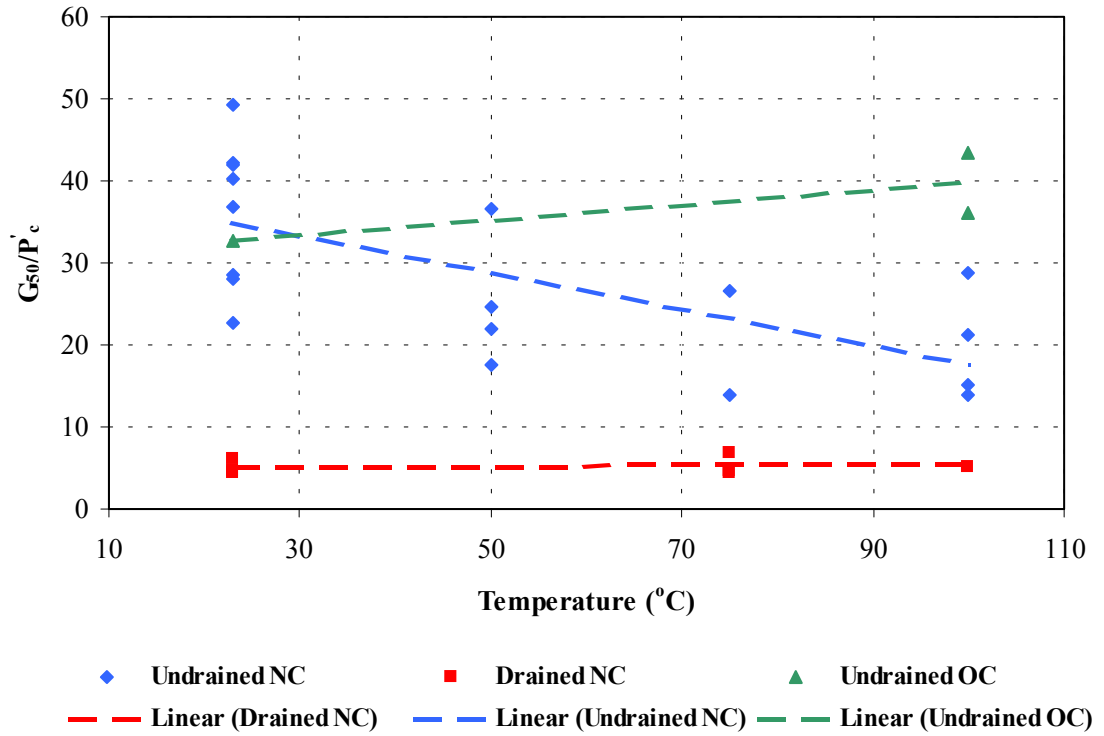


Figure 4.32 Changes in the drained stiffness of NC samples with temperatures

In another attempt to present the effects of temperature on stiffness, values of the normalized secant modulus at 50% of the maximum deviator stress, G_{50}/p'_c , are plotted versus temperature in Figure 4.33. There is considerable scatter within the undrained stiffnesses of normally and over consolidated samples at a certain temperature. If trend lines are drawn through all three sets of data, drained NC, undrained NC, and undrained lightly OC ($OCR = 2.5$), the overall trends demonstrate a reduction in G_{50}/p'_c for the undrained NC group and a slight increase for the undrained OC group with increase in temperature. The drained NC group present little influence of temperature on G_{50}/p'_c and are nearly constant at all temperatures. This is a consequence of the greater strain level at which G_{50} is determined. Figure 4.32 shows all curves converging at $\epsilon_s \approx 1\%$.



4.33 Changes in G_{50}/P'_c with temperature for samples of M44 clay

4.2.2.5 Critical state and cam-clay parameters

According to the theory of critical state soil mechanics, all the soil samples will eventually reach an ultimate state in which plastic shearing continues indefinitely without any changes in volume or effective stresses (Wood 1990). The ultimate points of drained and undrained triaxial compression tests should form a line, which passes through the origin. The equation of this line in the q - p' plane can be written as follow:

$$q = Mp' \quad (4.28)$$

Where q is deviator stress, p' is the mean effective stress and M is a soil constant. Not all samples have reached a critical state and some failed in earlier stages while developing shear zones. A method to check whether a sample has reached the critical state or not is to plot the stress ratio, q/p' , versus plastic strain ratio, $\Delta\varepsilon_v^p / \Delta\varepsilon_s^p$, at failure (Wood 1990). In an undrained test, the plastic and elastic volumetric strain increments are equal but opposite in sign, and $\Delta\varepsilon_s = \Delta\varepsilon_a$. Figure 4.34 shows the failure points of all tests with different colouring for each temperature. The green, blue, red, and magenta represent temperatures of 22°C , 50°C , 75°C and 100°C respectively.

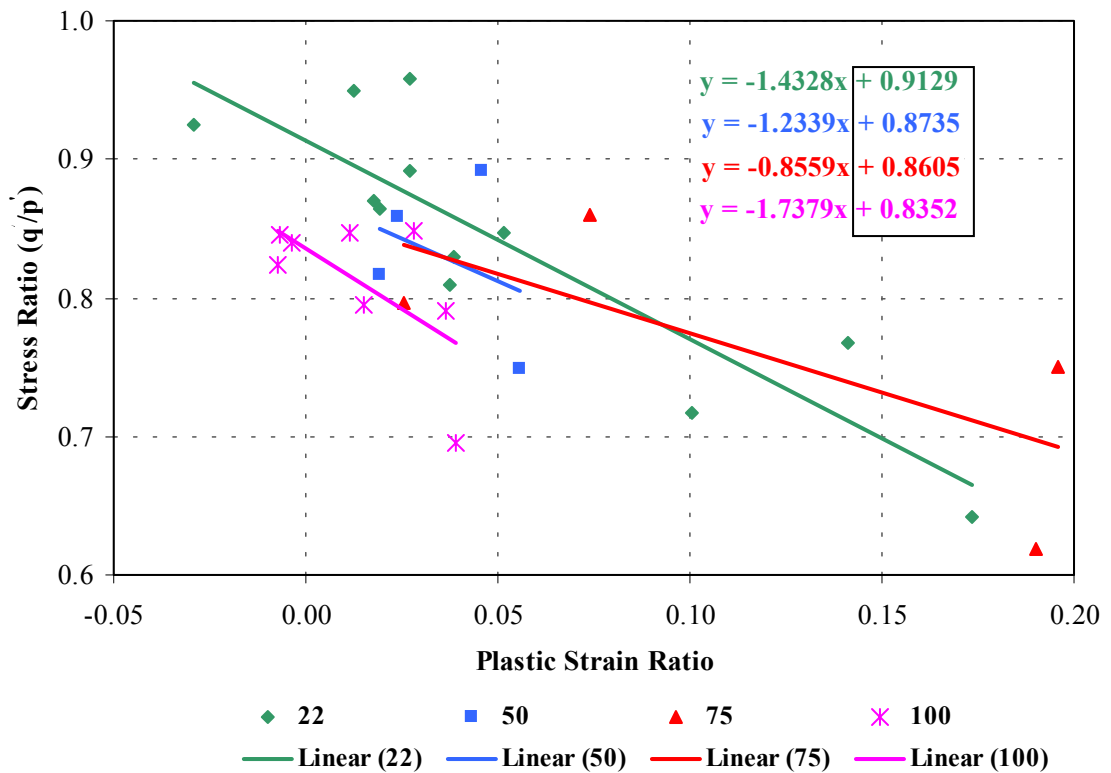


Figure 4.34 Changes in the stress ratio with plastic strain ratio at different temperatures

The intercepts of the best-fit lines, values of q/p' when $\Delta\epsilon_v^p / \Delta\epsilon_s^p = 0$, passing through each set of data indicate the M value at that temperature. It can be seen that the value of M reduces with an increase in temperature from 0.91 at 22°C to 0.83 at 100°C. Figure 4.35 illustrates the failure points given in Table 4.3 in the q - p' plane. The best-fit lines passing through the data (using a least squares method) at each temperature give another estimate of the critical state line at that temperature. It can be noticed that slope of the lines reduces with increase in temperature and that these slopes are less than the values of M estimated from Figure 4.34. This is consistent with the data in Figure 4.34 which shows that for most samples failure occurs before a critical state is reached.

Data from all tests showing the failure points together with isotropic normal consolidation lines at different temperatures in v - p' plane are presented in Figure 4.36.

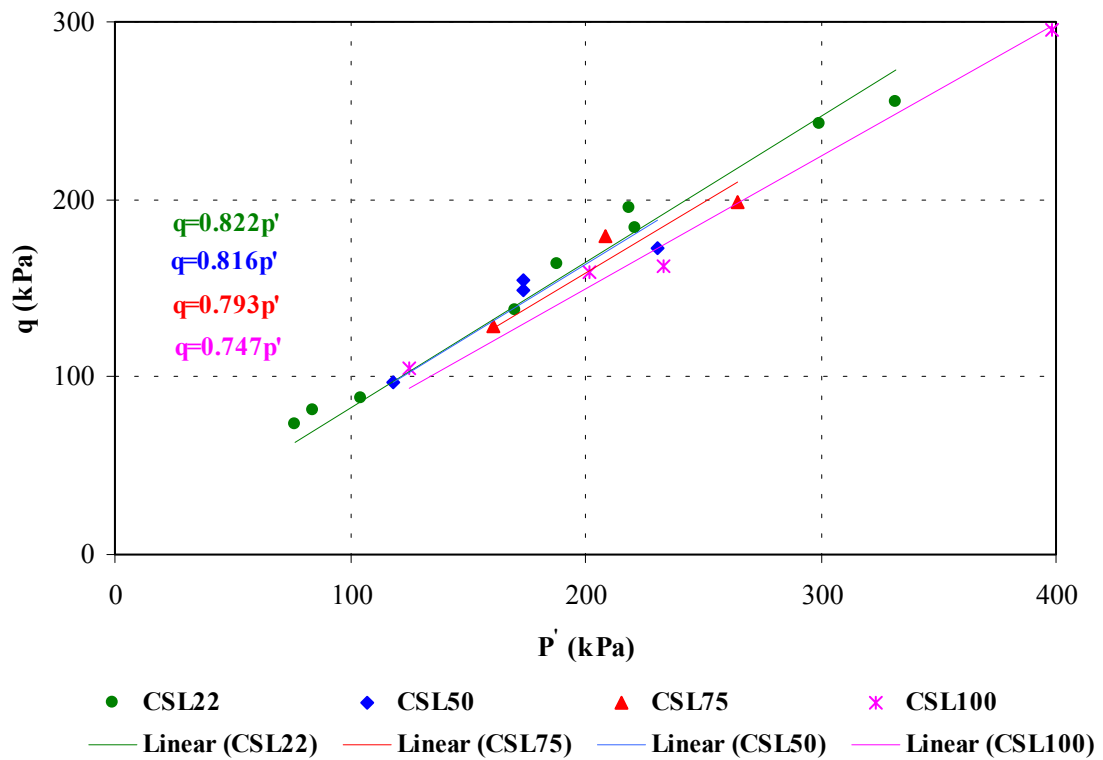


Figure 4.35 Failure states at temperatures between 22°C and 100°C

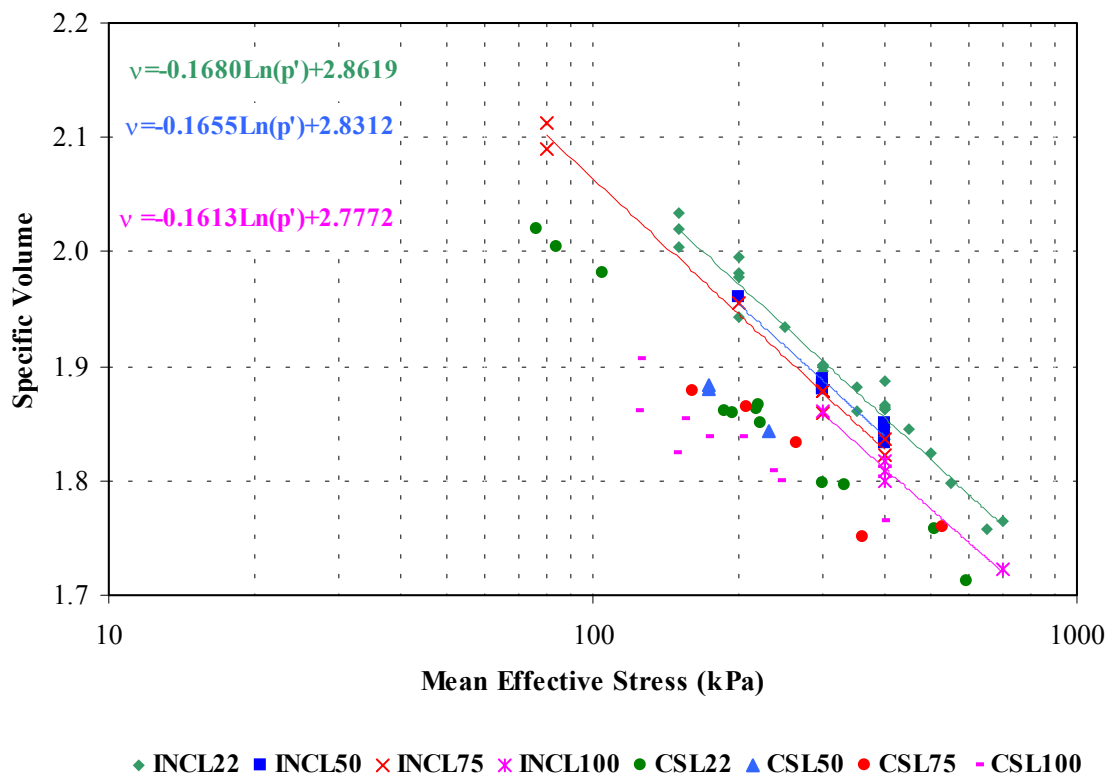


Figure 4.36 the results from all undrained and drained triaxial tests

It was previously shown in Figure 4.18 that the INCLs at various temperatures were parallel and were shifted down a certain amount due to temperature changes. With selection of failure points close to reaching a critical state and removal of the drained test results it can be seen in Figure 4.37 that the critical states lines at all temperatures can be drawn nearly parallel to the INCLs.

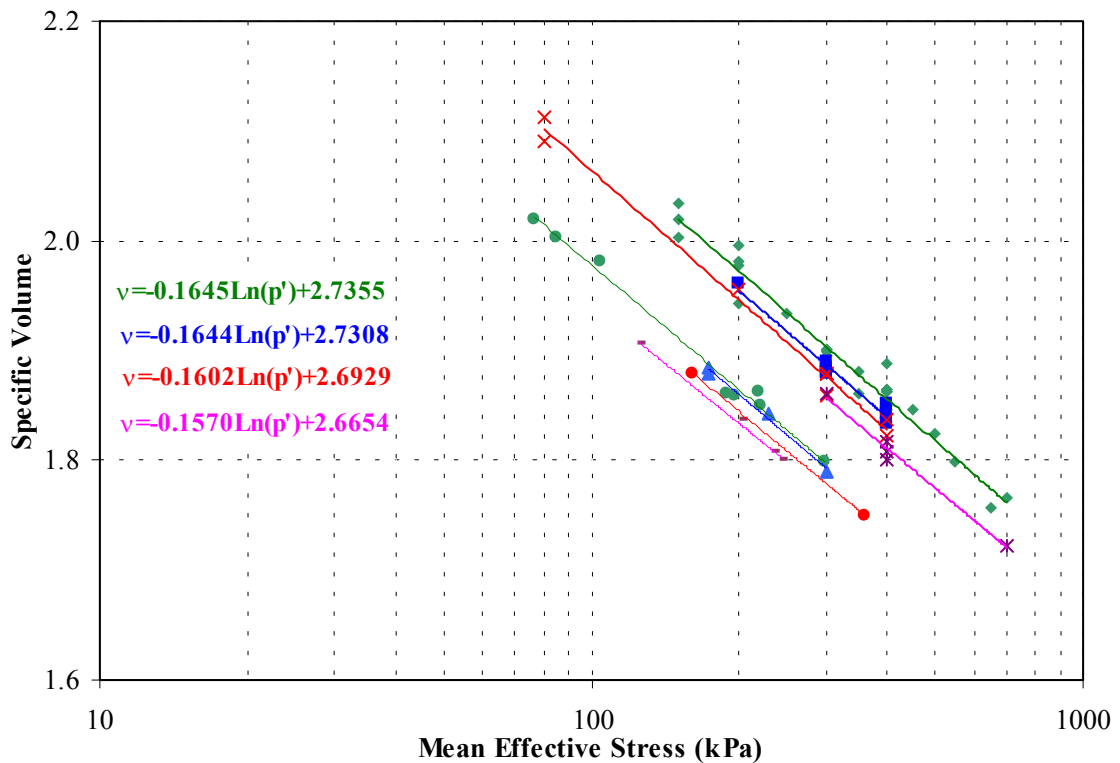


Figure 4.37 Normal consolidation and failure states of nearly all samples
(— 22°C, — 50°C, — 75°C, — 100°C)

It can be seen that the CSL has shifted downwards with increased temperature, similar to the shift in the INCL. Figure 4.38 shows the suggested INCLs and CSLs for M44 clay. The equation of each CSL is written next to it with the same colour.

Based on the available data it would be reasonable to consider that the shifts in the INCLs are equal to those in the CSLs. This assumption is used to simulate the thermo-mechanical behaviour of M44 clay in chapter 5.

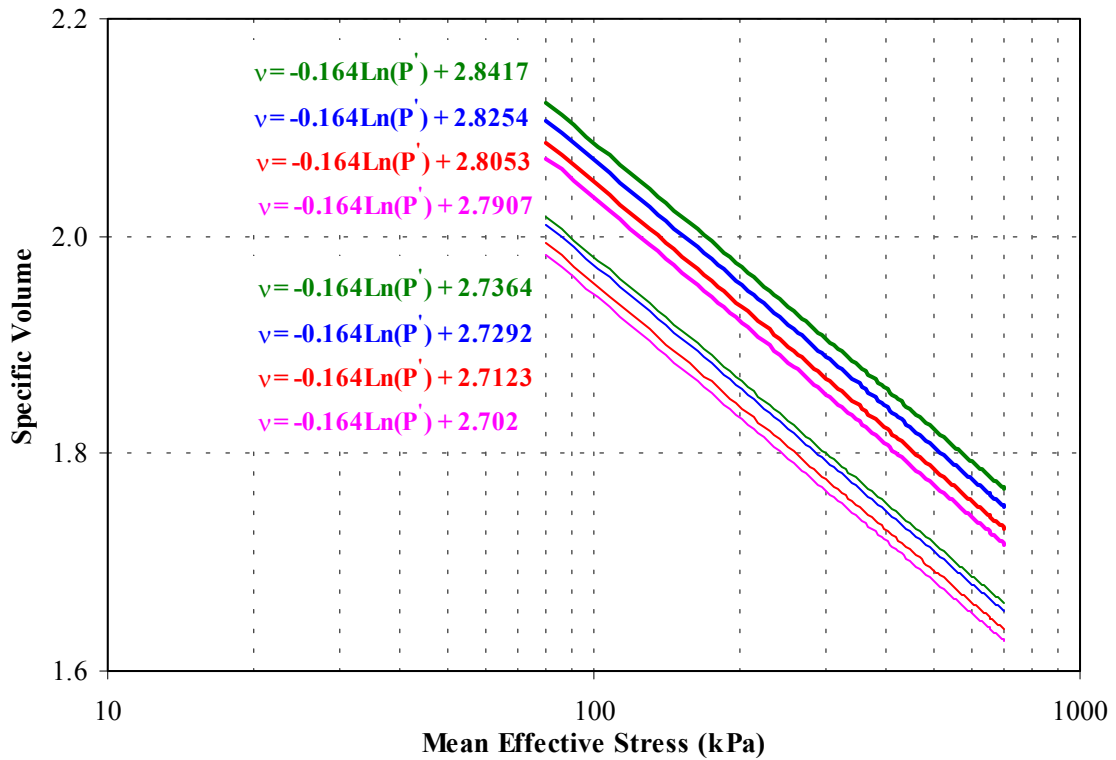


Figure 4.38 Suggested INCLs and CSLs (— 22°C, — 50°C, — 75°C, — 100°C)

The values of λ , N and M extracted from INCL and CSL equations together with other Cam-Clay parameters are summarized in Table 4.4. Values of 0.311 at 50°C and 0.0293 at 75°C for κ were calculated from interpolation of the values at 22°C and 100°C.

Table 4.4 Cam Clay Parameters of M44 Clay

Temperature °C	M	N	λ	Γ	κ	μ	G/p'_c
22	0.9	2.8417	0.164	2.7364	0.033	0.25	135
50	0.87	2.8254	0.164	2.7292	0.0311	0.25	135
75	0.86	2.8053	0.164	2.7123	0.0293	0.25	85
100	0.83	2.7907	0.164	2.7020	0.0275	0.25	35

4.2.3 Results of tests on Kaolin C1C

4.2.3.1 Isotropic mechanical and thermal consolidation

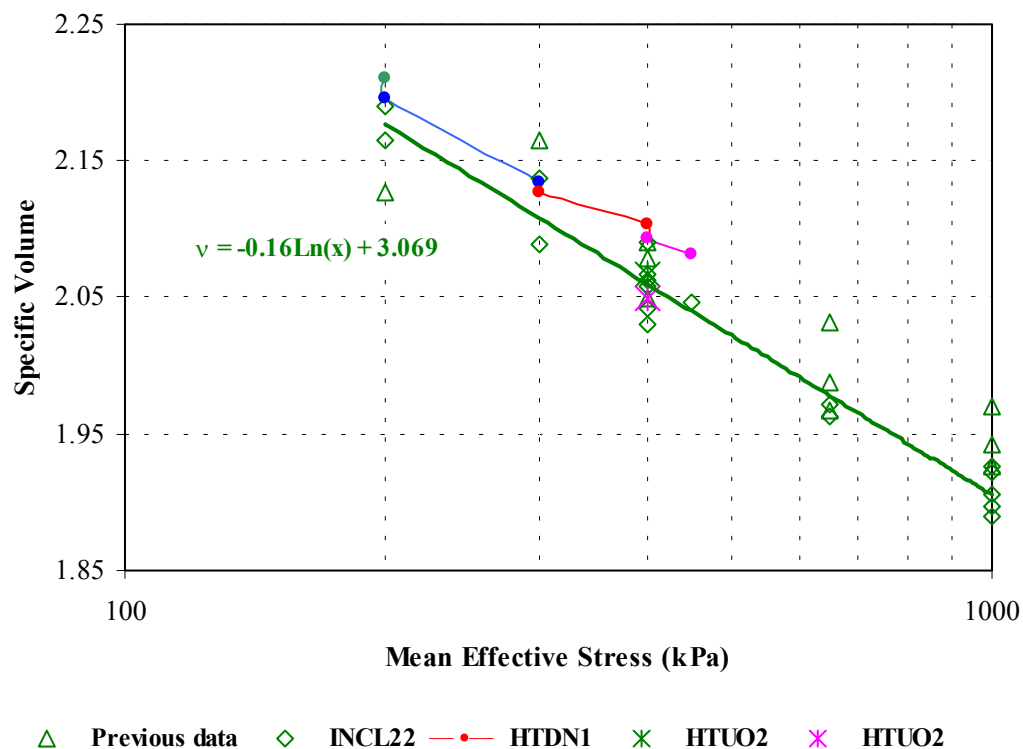
The thermomechanical consolidation data from tests on Kaolin C1C are summarized in Table 4.5. The rate of heating has never exceeded 0.1°C/min and the rate of mechanical loading and unloading in most cases was set under 0.25 kPa/min.

Table 4.5 results of Kaolin C1C consolidation.

Sample No.	Temperature (°C)	P' _c (kPa)	v _c	Comments
RTUN2	22	400	2.0899	
RTUN3	22	400	2.0298	
RTUN4	22	650	1.9635	
RTUN5	22	200	2.1652	
RTUN6	22	300	2.0884	
RTDN7	22	300	2.1379	
RTDN8	22	400	2.0623	
RTUN9	22	200	2.1894	
RTUN10	22	1000	1.8899	
RTUN11	22	1000	1.9224	
RTUN12	22	400	2.0666	Started to use radial strips
RTUN14	22	400	2.0574	
RTUN15	22	400	2.0417	
RTUN16	22	650	1.971	
RTUN17	22	1000	1.9055	Slightly disturbed
RTDN18	22	450	2.0466	
RTDN19	22	1000	1.9263	
RTUO20	22	1000-75	1.8972	
HTDN1	22	200	2.2101	Path D
	50	200	2.1953	
	50	300	2.1344	
	75	300	2.1268	
	75	400	2.1038	
	100	400	2.0936	
	100	450	2.0812	
HTUO2	22	400	2.0663	Path I
	50	268	2.0839	
	75	175	2.1110	
	100	112	2.1470	
	100	400	2.0491	
	100	50	2.1363	

It can be noticed that only two samples were tested at elevated temperature. The thermo-mechanical consolidation paths followed by samples HTDN1 and HTUO2 are paths D and I (Figure 4.2) respectively. Sample HTDN1 was initially consolidated to $p' = 200$ kPa then was heated from room temperature (22°C) to 50°C under drained conditions before consolidation to $p' = 300$ kPa. Subsequently the sample was thermally consolidated to 75°C followed by mechanical consolidation to $p' = 400$ kPa before drained heating to 100°C. Sample HTUO2 was initially consolidated to $p' = 400$ kPa then was heated undrained from 22°C to 100°C before drainage was allowed. Then it was overconsolidated by reduction of effective stress to $p' = 50$ kPa at 100°C implying an OCR of 8.

The values of specific volume after consolidation are plotted versus logarithm of effective stress, p' , during consolidation in Figure 4.39. The green, blue, red and magenta colours represent 22°C, 50°C, 75°C and 100°C respectively. The triangular green points are from the previous study on Kaolin C1C at room temperature (Chiu, 1996). The complete thermo-mechanical consolidation path for sample HTDN1 (path D) has been drawn with different colours indicating respective consolidation temperatures.



4.39 Results from isotropic compression of Kaolin C1C samples (— 22°C, — 50°C, — 75°C, — 100°C)

A linear least squares line was fitted to the room temperature points and values of N and λ at 22°C were determined to be 3.069 and 0.160 respectively. The data show some scatter that could be the result of creep and the different initial specific volumes at the beginning of consolidation. Chiu (1996) reported $c_\alpha = 0.006$ for samples of Kaolin C1C and suggested that the effects of creep were insignificant. The smaller drained thermal volume changes of Kaolin C1C observed (in Chiu, 1996 and this study) compared to M44 clay might be related to a lower sensitivity of Kaolin to temperature changes. It

has been claimed by Jefferson (1994) that a higher thermal sensitivity leads to a greater influence of temperature on soil properties.

Although all the samples were prepared in exactly the same way and values of specific volume were calculated from the final moisture contents of specimens, there was significant scatter observed in the initial values. This also was reported by Chiu (1996). It can be seen that the previous room temperature data points show similar scatter to the room temperature data in this study. As the same method was used as for M44 clay, the more significant scatter in the results for Kaolin C1C could be related to the type of clay itself. Although there is a small shift due to temperature in the specific volumes of sample HTDN1 it is not clear from Figure 4.39 whether or not the elevated temperature has caused a parallel shift in the INCL to a lower location in the v - p' plane. As mentioned in chapter 3, Chiu's data at elevated temperature were influenced by leakage from the drainage line and therefore any comparison might involve some error. In presenting his data Chiu (1996) adjusted the specific volumes at room temperature of all tests to lie on the same INCL in order to reduce the scatter and clarify the effects of temperature. He concluded that a parallel shift in the INCL with an increase in temperature occurred for Kaolin C1C although his results did not convincingly show this phenomenon. A similar approach has been used here to reduce the scatter in the room temperature data and is shown in Figure 4.40. The first point of test HTDN1 at $p' = 200$ kPa was adjusted to lie on the suggested INCL and the rest were plotted accordingly. Sample HTUO2 has been presented with only two points corresponding to thermal consolidation at 22°C and at 100°C when undrained heating had finished and drainage was allowed. It can be seen that the point at 100°C is clearly under the INCL at 22°C. The path followed by sample HTDN1 passes through points at 50°C that are nearly parallel to INCL22 but at 75°C and 100°C, the curve crosses the INCL22 line. This suggests that the INCL for Kaolin C1C is independent of temperature and that the effects of the thermal consolidation after each step of heating have been removed by the subsequent mechanical consolidation. This type of behaviour was not observed in M44 clay, however there were no tests that followed a similar path. Similar behaviour has been reported by Towhata et al (1993b) for samples of MC Kaolin during oedometer tests at temperatures ranging from 22°C to 90°C. They suggested that the effects of heating was removed by further mechanical consolidation to higher effective stresses. This type response known as a "thermal over consolidation effect" was also observed by

Sultan (1997) for intact samples of Boom clay, and Cui et al (2000) modelled this effect considering that the mechanical consolidation followed by thermal consolidation has a lower slope than λ but higher than κ .

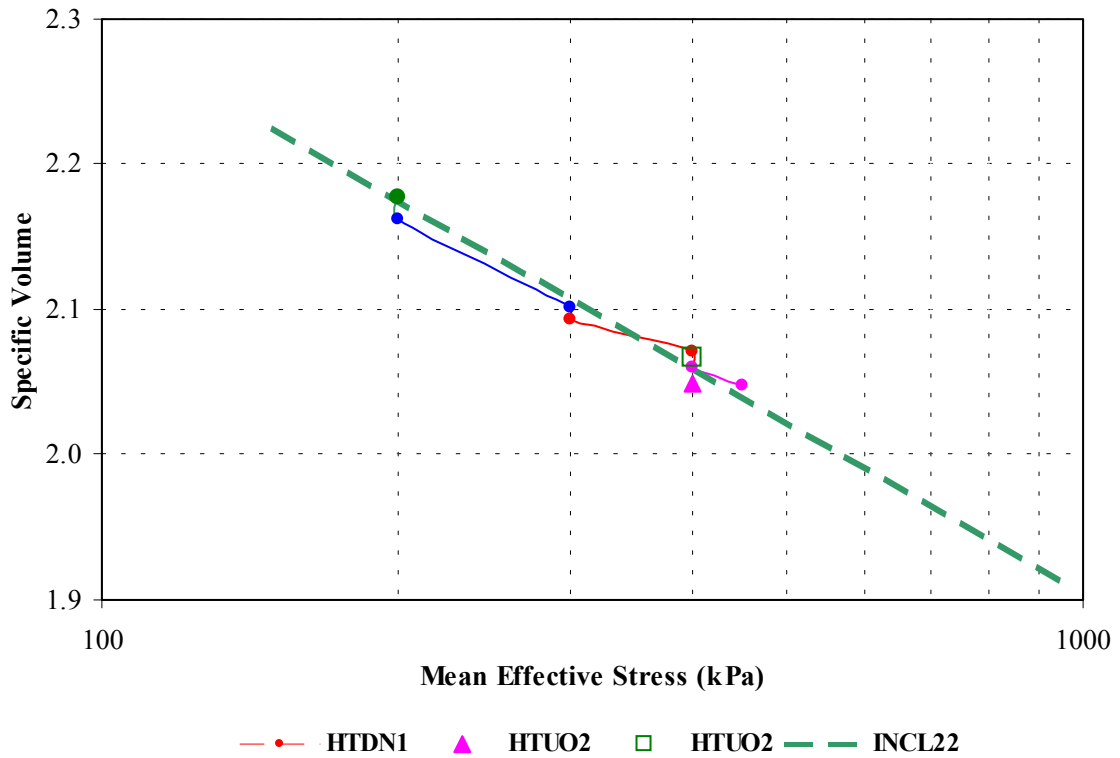


Figure 4.40 Isotropic compression of Kaolin C1C (— 22°C, — 50°C, — 75°C, — 100°C)

During consolidation the sample's volume changes were measured by both GDS and internal transducers. The consolidation path of sample HTDN1 in the v - T plane is depicted in Figure 4.41. The specific volume determined from the LVDTs are based on the conversion factors reported in Table 4.1 for M44 clay because no room temperature test with the use of internal measurements was available for Kaolin C1C. It can be seen that the calculated changes of specific volume from the LVDTs are slightly higher than those calculated from the GDS. These differences in the observed values might be related to the application of similar factors as M44 clay which may not be accurate enough. To show the effects of increasing temperature the intermediate sections of mechanical loading have been removed and the thermal volumetric strains (from GDS) are plotted in Figure 4.42 at different temperatures. NC Kaolin C1C shows a volume contraction of about 1.2% upon heating from 22°C to 100°C and variations of

volumetric strain with temperature appears to be almost linear. This may be compared with strains of $\sim 2.2\%$ for M44 clay (see Figure 4.7).

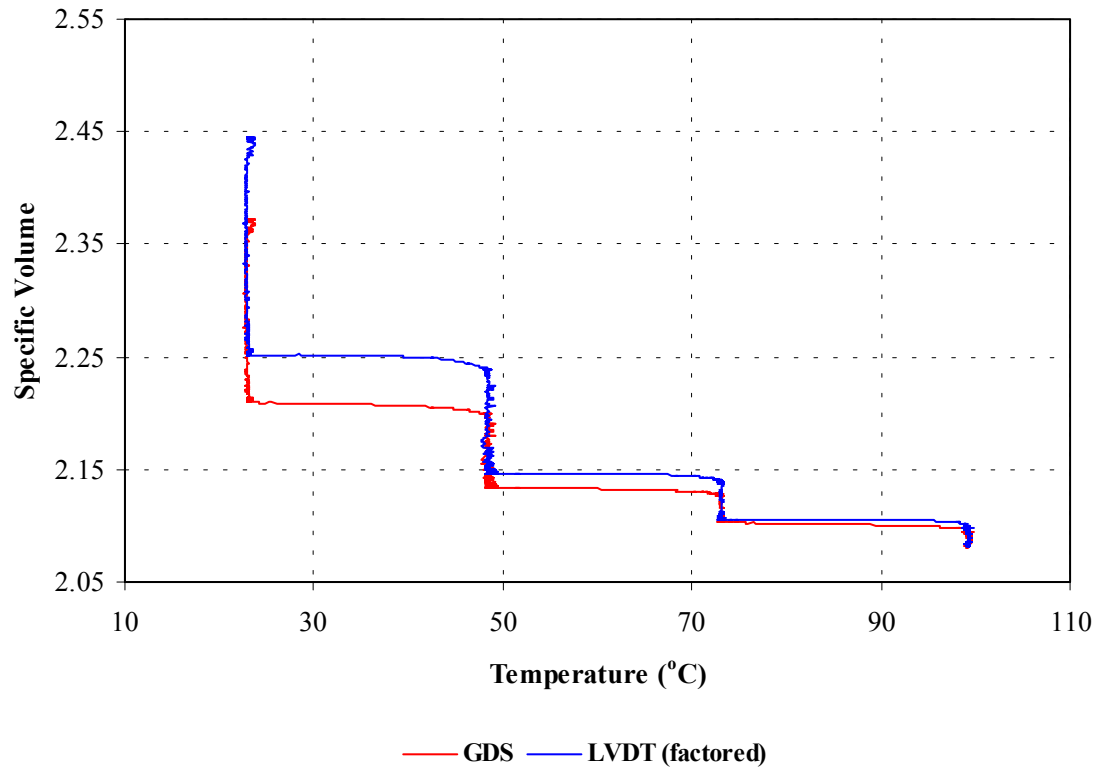


Figure 4.41 Changes in Specific volume with temperature for Kaolin C1C (HTDN1)

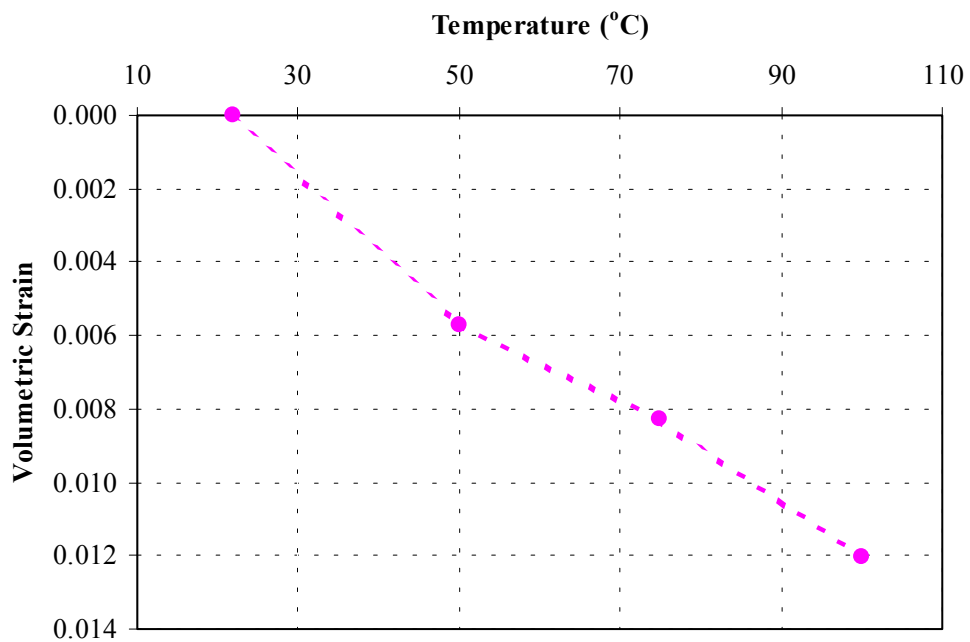


Figure 4.42 Changes in volume strain with temperature for Kaolin C1C (HTDN1)

Figure 4.43 shows the isotropic compression and swelling lines in two different tests at 22°C and 100°C. The rate of loading and unloading was 0.25 kPa/min in both tests. The compression parts of both samples were at room temperature. The green and magenta lines are swelling curves at 22°C and 100°C respectively.

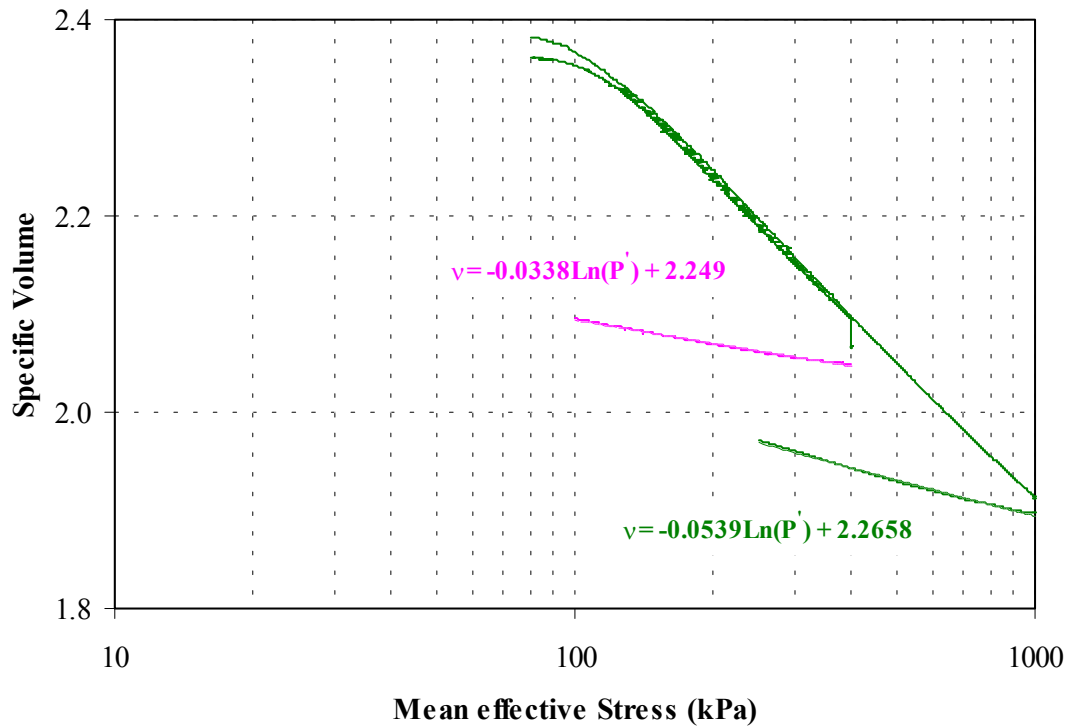


Figure 4.43 Isotropic unloading-reloading curves for Kaolin at 22° C and 100°C (— 22°C, — 100°C)

It is often considered that the relationship between v and natural logarithm of effective stress is linear. It is clear from Figure 4.43 that the slope of the swelling curve is increasing with reducing effective stress. For the purpose of comparison at different temperatures the unloading-reloading curve was considered to be linear for a certain range of effective stress. In order to avoid the effects of different initial p'_c , a straight swelling line has been drawn from the beginning of unloading to the point at which the effective stress corresponds to $\text{OCR} = 4$. The result shows that the slope of swelling line is reduced from 0.0539 at 22°C to 0.0338 at 100°C. In contrast, Chiu (1996) reported that the slope of swelling line remained unchanged at elevated temperature. This apparent inconsistency might be related to either leakage in the system or his method of determination method of the swelling line. He has estimated the value of κ from the

initial slope of unloading-reloading curve. M44 clay has also shown a reduction in κ at elevated temperatures. Campanella and Mitchell (1968) also showed a slight reduction in κ with temperature for samples of Illite. It is believed from tests on both clays that the slope of swelling curve reduces with increase in temperature.

4.2.3.2 Coefficient of volumetric thermal expansion of Kaolin particles

α_s , the coefficient of volumetric thermal expansion of solid, was calculated from the same procedure as has been explained for M44 Illitic clay in section 4.2.2.2. The results are summarized in Table 4.5. Due to timing limitations only two high temperature tests were carried out on Kaolin C1C, HTUO2 and HTDN1. The remaining proximity gauge was not available in the above two tests and the volumetric strain was determined using the axial strain determined from the LVDTs and equation 4.25 considering $\varepsilon_v = 1.65\varepsilon_a$ similar to undrained heating tests on M44 clay. The value of α_s for temperatures above 75°C is calculated to be $2.5 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$, which is slightly lower than the value of $3.5 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ reported by Campanella and Mitchell (1968). This difference in α_s might be the consequence of non-uniform deformation of sample during undrained heating, an error in the accuracy of the measuring devices and from some physico-chemical changes in the sample.

Table 4.5 The result from undrained heating (HTUO2)

Temperature (°C)	22-50	22-75	75-100
α_s (factored LVDT)	0.000019	0.000031	0.000025

Similar to M44 clay, thermal volumetric strains and volume changes during thermal consolidation were corrected using the value of $\alpha_s = 3.5 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$. For a reasonable determination of α_s an accuracy of $\pm 10 \text{ } \mu\text{m}$ or better is needed for measurement of radial displacement. This type of accuracy at elevated temperature under water needs improvements in the small displacement measuring devices technology. The α_s of minerals are usually measured using X-ray techniques such as those presented by McKinstry (1965). To the author's knowledge this is the second time that an attempt has been made to measure a soil's coefficient of thermal expansion directly during triaxial tests. Chiu (1996) failed to measure α_s properly due to failure of the PGs and their calibration problems, which he used for both axial and radial displacement

measurement. The use of internal LVDTs in this study has improved the measurement reliability of axial strain, but problems still remain with radial displacement measurement.

4.2.3.3 Shearing characteristics of Kaolin C1C

The results from undrained and drained triaxial shear tests at different temperatures on Kaolin C1C are shown in Table 4.6. Most of the samples, especially in drained tests, failed by developing rupture planes at relatively low strains. The first two letters in the specimen number show the temperature, room temperature (RT) or high temperature (HT), the third letter displays the drainage condition during shearing which is either drained (D) or undrained (U), the fourth letter indicates if the sample is normally consolidated (N) or over consolidated (O) and finally is the test number.

Table 4.6 Results from drained and undrained shear tests on Kaolin C1C

Sample No.	Temperature °C	p'_c (kPa)	q_f (kPa)	p'_f (kPa)	v_f	G/p'_c	G_{50}/p'_c
RTUN2	22	400	185.1	238.1	2.0899	41.6	18.8
RTUN3	22	400	196.1	240.6	2.0298	26.6	12.1
RTUN4	22	650	306	421.5	1.9635	22.2	13.4
RTUN5	22	200	91.5	108.7	2.1652	23.6	14.4
RTUN6	22	300	144	163.4	2.0884	32.1	25.3
RTDN7	22	300	306	401	1.9818	17.9	5.2
RTDN8	22	400	308.6	501.9	1.9289	27.3	5.5
RTUN9	22	200	86.4	113.7	2.1894	16.1	10.8
RTUN10	22	1000	430.1	616.4	1.8899	26.2	10.2
RTUN11	22	1000	461.2	596.7	1.9224	20.3	10.6
RTUN12	22	400	169.3	237.4	2.0666	16	11
RTUN14	22	400	162.5	211.2	2.0574	29.1	11.5
RTUN15	22	400	187.2	241.4	2.0417	29.3	12.8
RTUN16	22	650	259.8	364.4	1.971	28.3	7.67
RTUN17	22	1000-75	398	590.1	1.9055	39.96	9.52
RTDN18	22	450	367	572.3	1.9224	25.1	4.3
RTDN19	22	1000	795.3	1262.5	1.8015	30	3.9
RTUO20	22	125	108.1	164.9	2.0531	30.5	9.8
HTDN1	100	450	406.1	586.4	1.9788	15.9	6.3
HTUO2	100	400-50	105.6	93.2	2.1363	313.6	41.2

Figure 4.44 illustrates the relationship between normalized deviator stress and axial strain during drained shear tests. The green and magenta colours represent temperatures of 22°C and 100°C respectively. The hollow diamond points present the end points from

the previous study on Kaolin C1C (Chiu 1996). The room temperature curve is a typical drained stress-strain response. The deviator stress has been normalized by the mean effective stress at the end of consolidation, p'_c . It is clear that the strength of Kaolin C1C at 100°C is slightly higher than at room temperature. By careful examination of the data in table 4.6, it can be noticed that despite some scatter in the values of normalized initial shear modulus (G/p'_c) the overall trend indicates a reduction in G/p'_c from about 30 at 22°C to 15.9 at 100°C. As can be seen from Figure 4.45 the volumetric strains at 100°C are slightly lower than at 22°C, the axial strain at failure is lower, and the sample presents a less ductile response to stress change at higher temperatures. Chiu's results showed the same pattern but his results indicated significantly lower volumetric strain at failure because of problems with leakage.

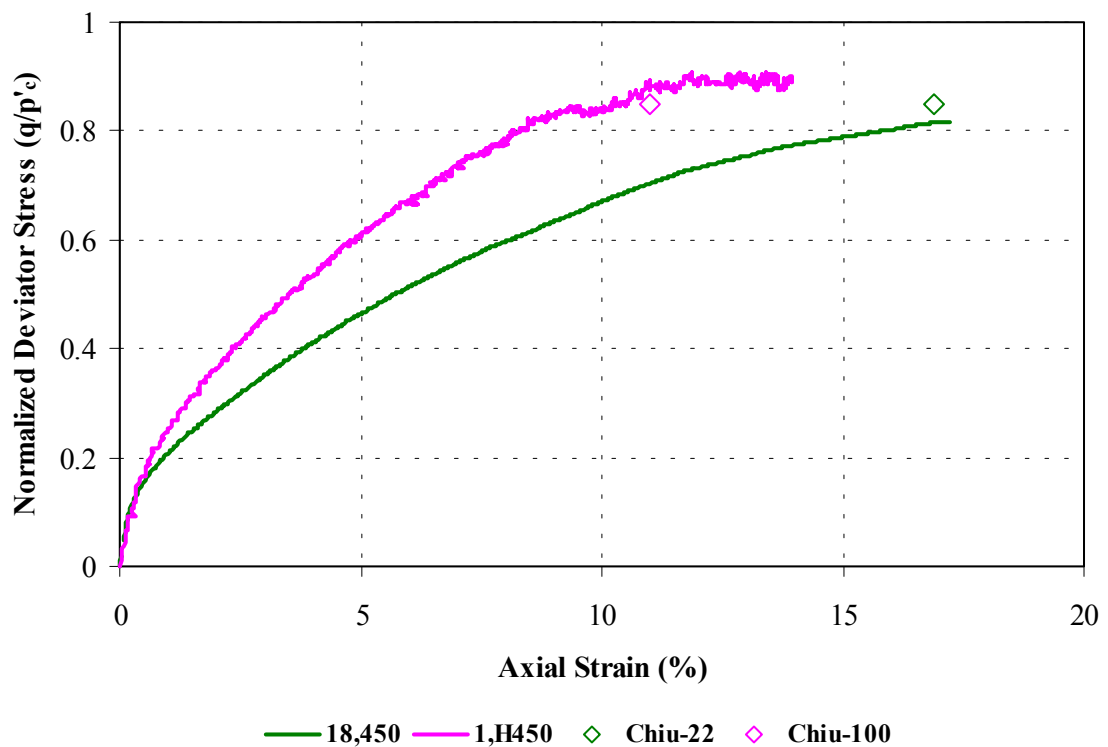


Figure 4.44 Stress-strain response of Kaolin C1C during drained test (— 22°C, — 100°C)

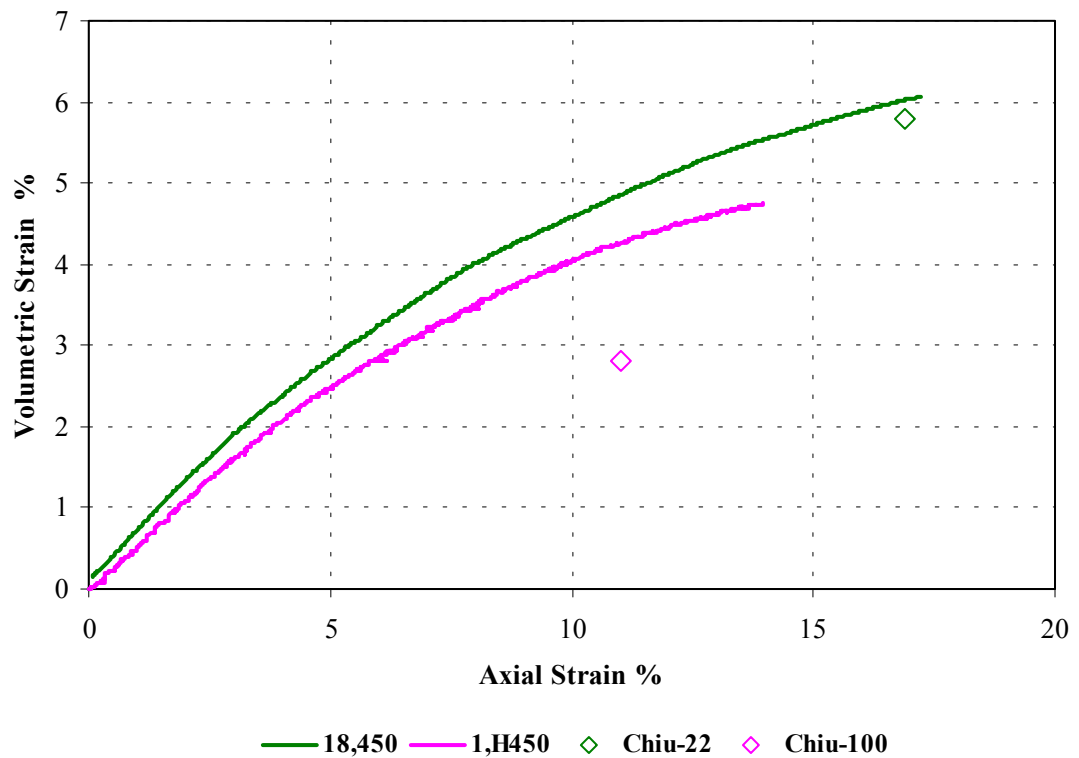


Figure 4.45 Variations of volumetric strains during drained triaxial tests on Kaolin C1C samples
(— 22°C, — 100°C)

Considering the results from M44 clay and Kaolin C1C (previous and current), a consistent trend is observed indicating that during drained triaxial tests at elevated temperature NC samples of both clays present lower initial shear modulus, but a more brittle response, higher drained shear strength and lower volumetric strain at failure.

The value of Poisson's ratio was calculated to be 0.2 (equation 4.27). This seems low compared to other reported values of around 0.3 for clay, and could be related the more sensitive internal measurement of axial strain.

A typical result from an undrained triaxial shear test at room temperature is plotted in Figures 4.46, 4.47 and 4.48 together with the end points from Chiu (1996) for undrained tests at elevated temperature. It should be noted that the room temperature tests on Kaolin C1C were carried out in a conventional triaxial machine without any internal displacement measuring devices and the results have been slightly modified to allow for initial bedding error.

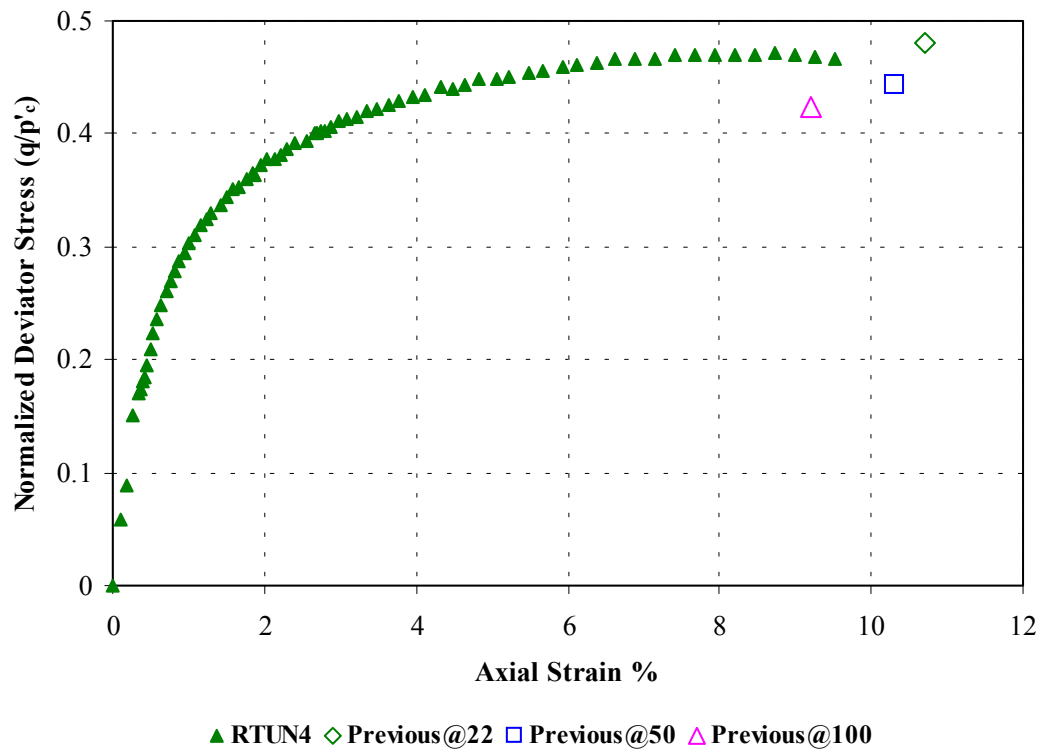


Figure 4.46 Stress-strain response to undrained loading at room temperature

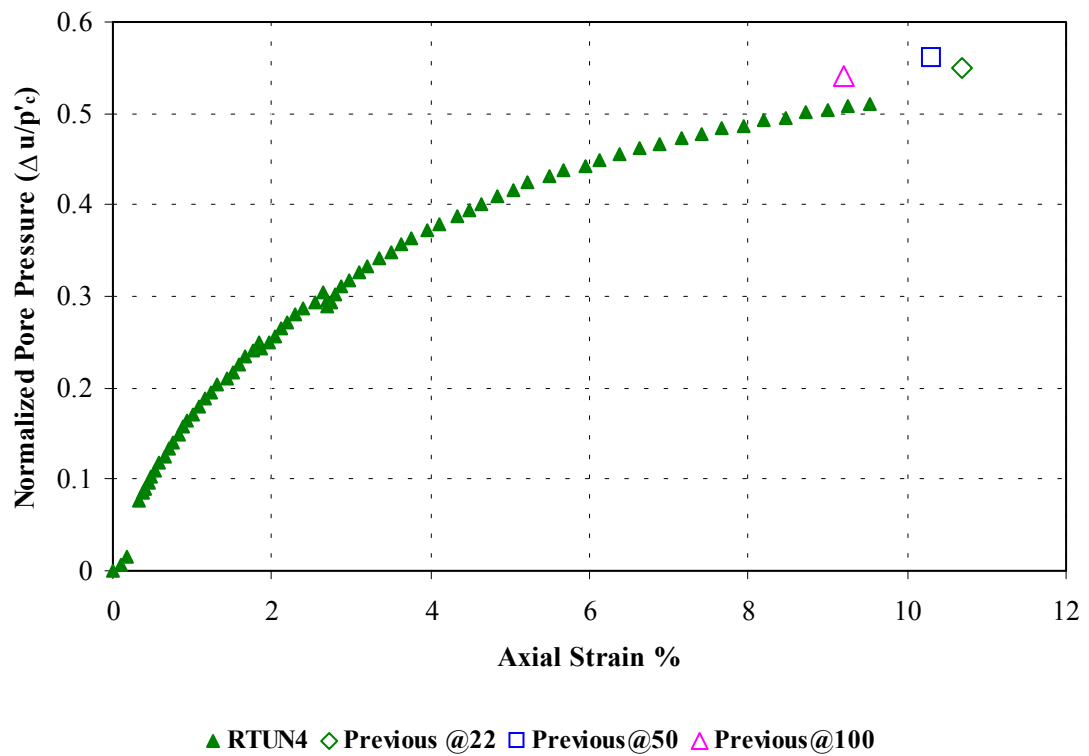


Figure 4.47 Pore pressure changes during undrained shear test on NC samples

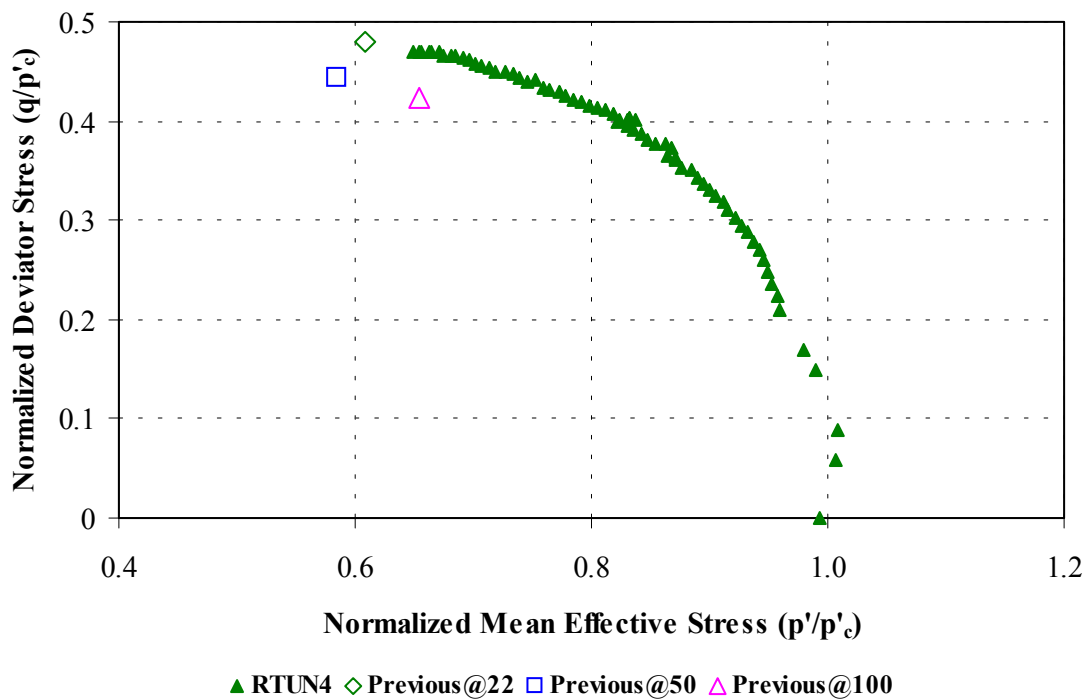


Figure 4.48 Stress paths for undrained shear test on NC samples

The current room temperature results are in reasonable agreement with Chiu's results except that they present slightly lower axial strain. This might be related to the use of a different type of triaxial apparatus by Chiu (hydraulic triaxial apparatus). Chiu's results at 50°C and 100°C show slightly lower shear strengths than at 22°C. This trend is similar to that for M44 clay and it is suggested that undrained shear strength decreases at elevated temperature for NC clays. Confirmation of this hypothesis for Kaolin C1C requires further investigation because Chiu (1996) shows only a very slight effect. The development of normalized pore pressure is similar in all tests at different temperatures, as it was for M44 clay (Figure 4.23). Figure 4.48 is a typical stress path and demonstrates the changes in normalized deviator stress against the normalized mean effective stress. Considering the fact that pore pressure development remains essentially unchanged and the maximum deviator stress at failure slightly reduces due to heating, it might be concluded that the slope of CSL, M , also decreases at elevated temperature. This pattern was clearly identified for M44 clay but it is not very clear here. The undrained stress-strain paths from the previous study (Chiu, 1996) on Kaolin C1C are

shown in Figures 4.49, 4.50 and 4.51. The responses are all similar to the room temperature response found in the current study.

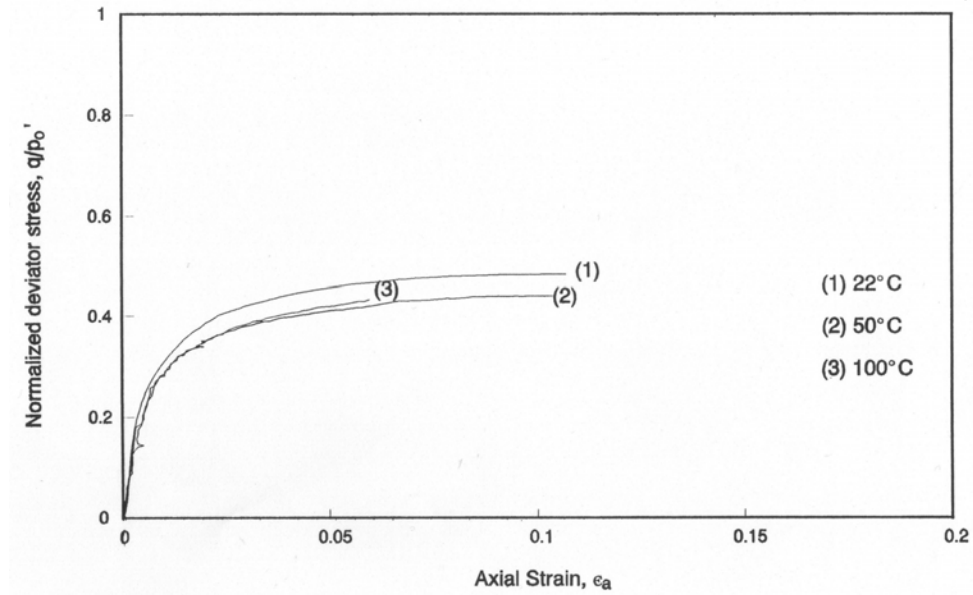


Figure 4.49 Stress-Strain response of NC Kaolin C1C during undrained shear tests (after Chiu 1996)

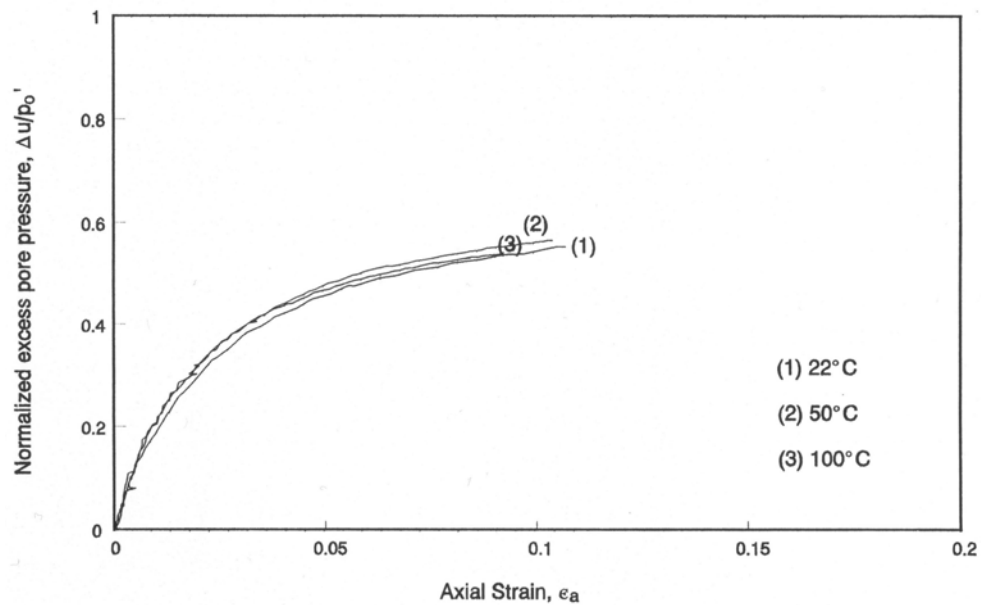


Figure 4.50 Pore pressure development of NC Kaolin C1C during undrained shear tests (after Chiu 1996)

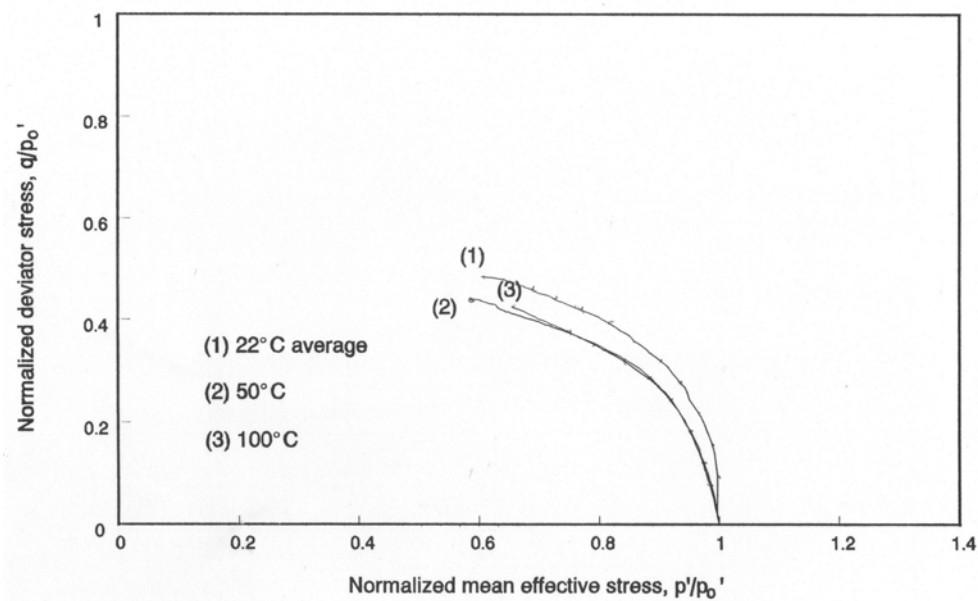


Figure 4.51 Stress Paths of NC Kaolin C1C during undrained shear tests (after Chiu 1996)

Due to time limitations only two tests on highly overconsolidated samples of Kaolin C1C, RTUO20 (OCR = 13) and HTUO2 (OCR = 8) were carried out. No direct comparison has been presented here because the samples had different OCRs and initial mean effective stresses, and more importantly the room temperature results were not considered reliable. The previous study of Chiu (1996) has also only presented tests on lightly overconsolidated (OCR < 2) samples. Therefore any comments on the temperature effects on the behaviour of overconsolidated (OC) samples of Kaolin C1C would require more experimental data. The results of undrained shearing of sample HTUO2 are reported in appendix 4.D.

4.2.3.4 Critical state and modified Cam clay parameters

As mentioned earlier in section 4.2.2.4, all the triaxial tests will eventually reach an ultimate state called the critical state. In order to find the CSL (critical state line), the effective stresses at failure of the recent and previous compression triaxial tests at different temperatures are plotted in Figure 4.52. In the legend letters R and P represent recent (current) and previous studies on Kaolin C1C.

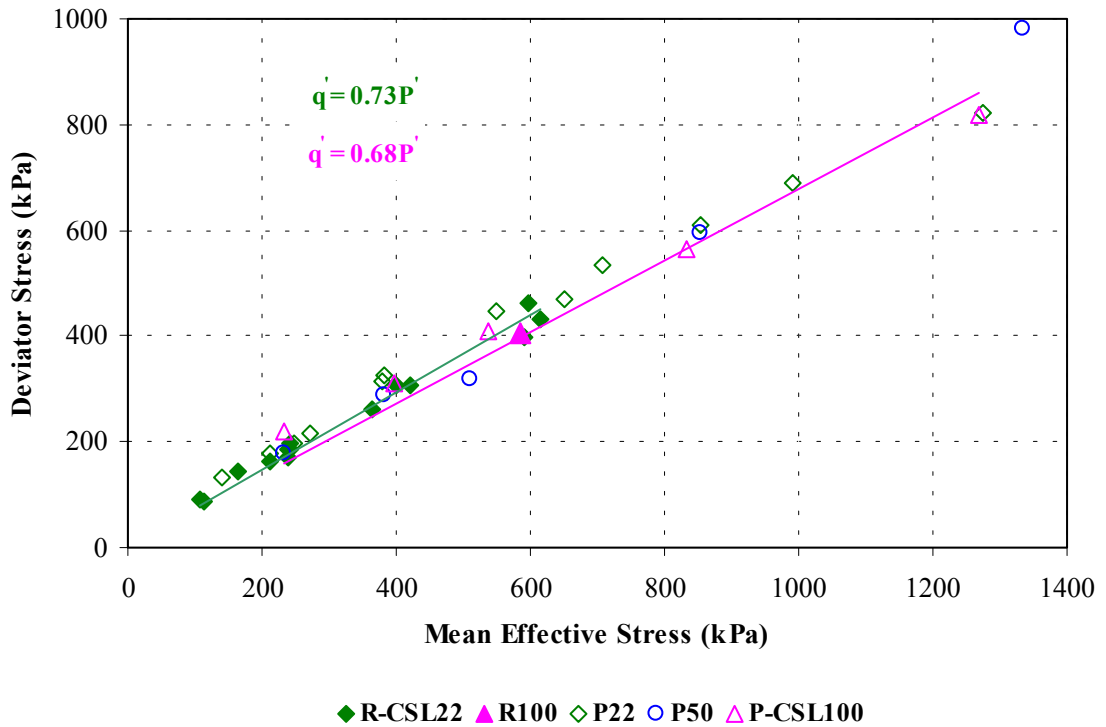


Figure 4.52 Failure states from drained and undrained shear tests on Kaolin C1C

It can be seen that the points from tests at elevated temperature (Chiu, 1996) are within the same range as the points at room temperature. The best-fit lines passing through the origin and the points at 22°C and 100°C give slopes equal to 0.73 and 0.68 respectively. As mentioned earlier, most of the samples failed with the development of shear planes and may not have reached a critical state. In order to determine whether the shear plane development has influenced M at 22°C, the stress ratios at failure, q_f/p'_f , are plotted versus plastic strain ratio, $\Delta\epsilon_v^p/\Delta\epsilon_s^p$, in Figure 4.53. As the sample reaches the critical state line, the plastic strain ratio is reducing to zero (Wood 1990). The line drawn through the points in Figure 4.53 crosses the q_f/p'_f axis at M equals to 0.8. This may be compared with $M = 0.73$ indicated in Figure 4.52. Following a similar procedure Chiu, 1996 found $M = 0.8$ for tests at 100°C. The apparent reduction in M shown in Figure 4.52 at elevated temperature is thus misleading for Kaolin C1C.

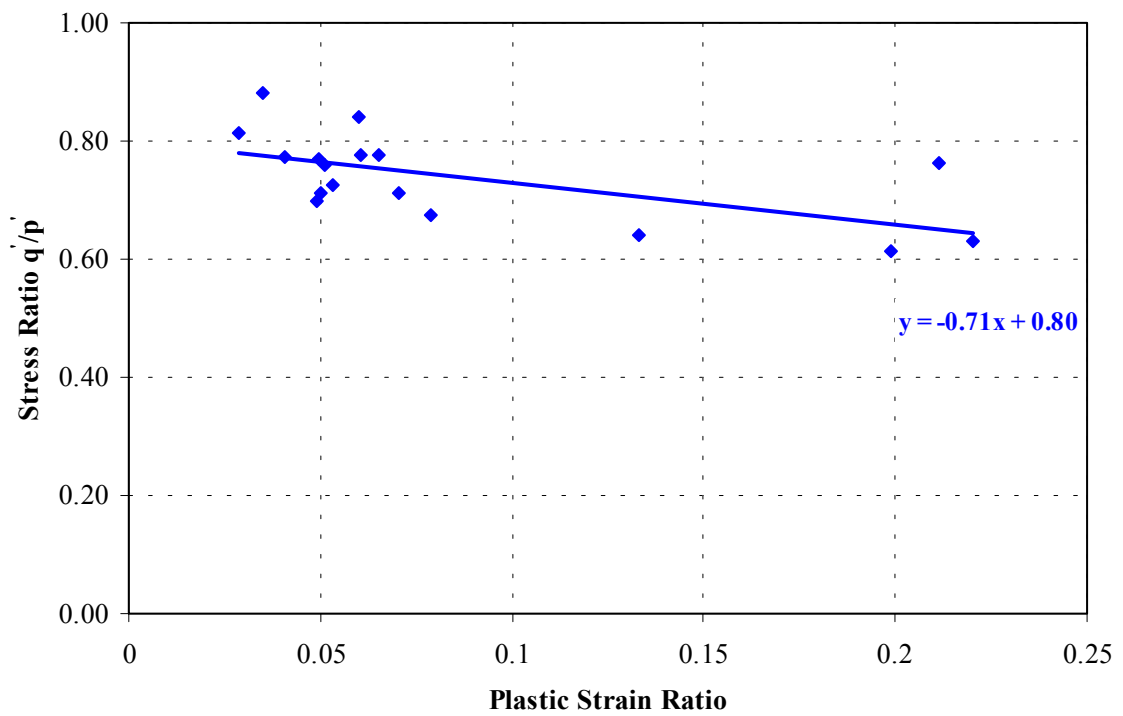


Figure 4.53 Variation of plastic strain ratio at failure

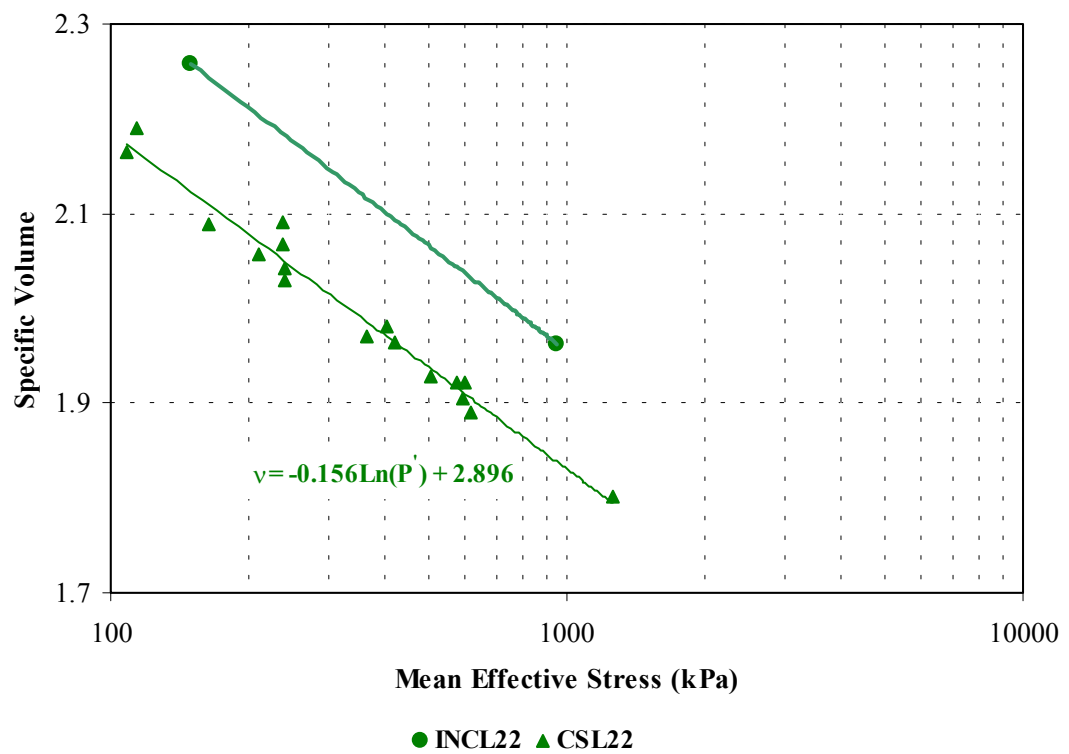


Figure 4.54 Isotropic compression and critical state of Kaolin C1C

A similar pattern was also observed for M44 clay and indicated a reduction in the slope of CSL in q - p' plane at elevated temperature. Despax (1976) has also claimed that heating causes a reduction in M value. To the author's knowledge the variations of M with temperature has not been often investigated and most researchers (e.g. Houston et al 1985, Hueckel and Baldi 1990, Graham et al 2001) have observed that M is constant and independent from temperature.

Figure 4.54 shows the trace of the critical state line at room temperature in the v - p' plane. The samples that failed far from the CSL have been eliminated. As expected, the CSL22 is nearly parallel to the INCL22, and the value of Γ , the specific volume at $p' = 1$ kPa, is 2.896. This value is in agreement with the findings of the previous study at room temperature. The modified Cam clay parameters for Kaolin C1C are summarized in Table 4.7.

Table 4.7 Cam Clay Parameters of Kaolin C1C

Temperature °C	M	N	λ	Γ	κ	μ	G_{50}/p'_c
22	0.8	3.06	0.16	2.9	0.0539	0.2	9.81*
50	0.75*	3.053*	0.16*	2.94*	0.0426	0.3*	8.86*
100	0.8*	3.04*	0.16*	2.94*	0.0338	0.3	10.26*

* These values have been extracted from Chiu's thesis (1996).

The results from Chiu show a small shift in the INCL due to heating in v - p' , which was not observed in the current study. The change in N is however much smaller than for M44 clay.

4.2.4 Comparison of the results with previous studies

It was shown in the literature review that the effects of temperature on shear strength and stiffness of soils is still controversial. Some of these controversies could be easily addressed by examination of the thermo-mechanical histories. For example, undrained heating followed by undrained triaxial shear tests definitely reduces the shear strength due to thermally induced pore pressure. The results from undrained shear tests on NC samples of M44 clay and Kaolin C1C both show that the undrained shear strength and initial normalized shear modulus decrease at elevated temperature. This is in agreement with the findings of Mitchell (1964), and Lingnau et al (1995) for NC samples with a history of drained heating. Unconfined compression tests on heated samples under undrained conditions in nearly all studies (e.g. Murayama 1969, Sherif and Burrous

1969) resulted in lower shear strength. In contrast Houston et al (1985) claimed an increase in the undrained shear strength of NC samples of an illitic rich sediment with a history of drained heating. As mentioned in chapter 2 the pattern of increasing shear strength was not clear in Houston et al's results for temperatures from 22°C to 100°C (see Figure 2.12) and only at 200°C was a high peak shear strength observed. This strengthening at 200°C might be related to physico-chemical changes in the soil, which have been reported for temperatures above 100°C for Illite (Graham et al, 2001). Kuntiwattanakul et al (1995) also reported that during isotropically consolidated undrained triaxial tests on NC samples of MC Kaolin clay heated under drained conditions, the shear strength and initial stiffness (at 0.1% axial strain) increased at elevated temperature. However, the strength of OC samples remained unaffected by temperature and only initial stiffness was increased. It was suggested by Jefferson et al (1996) that Kuntiwattanakul et al could have introduced some degree of anisotropy to their samples as the maximum effective stress in their tests was 196 kPa while the specimens had been previously one dimensionally consolidated to 98 kPa. It has been shown that the deformations are not isotropic in the current study and anisotropy seems unlikely as an explanation of different trends reported by Kuntiwattanakul et al.

Lightly OC samples of M44 clay demonstrated a similar trend to the NC samples indicating reduction of undrained shear strength and initial shear modulus at elevated temperature. The sequences of thermal and mechanical consolidation were found to have a significant effect on the maximum deviator stress reached during shear tests on highly OC (OCR = 7) samples of M44 clay.

The drained shear strength of NC samples of M44 clay and Kaolin C1C increased slightly with temperature while the ductility reduced. Hueckel and Baldi (1990) showed that shear strength and stiffness of highly OC samples of Pontida silty clay subjected to drained heating reduced with increase in temperature in drained triaxial tests while the shear strength of NC samples remained unaffected by temperature. The slope of CSL was found to reduce with temperature whereas it has been assumed in most studies to be temperature independent.

In agreement with nearly all previous studies (e.g. Campanella and Mitchell 1968, Graham et al 2001) the results from thermo-mechanical consolidation of M44 clay reveal that λ is independent of temperature while N , the specific volume at $p' = 1$ kPa,

reduces with increase in temperature. κ was found to be dependent on both effective stress and temperature for M44 clay and Kaolin C1C. It clearly reduced at elevated temperature

4.3 Hydraulic conductivity

The sample preparation, equipment and test procedure have been discussed in chapter 3, and only the results are discussed here.

4.3.1 Results

Constant head permeability tests were carried out only on M44 clay samples. As mentioned in chapter 3 a pressure difference of 20 kPa between the base and top of the sample was applied and the flow of water from the base to the top at different temperatures was measured. Figure 4.55 shows typical data for the cumulative flow of water into the base and out of the top of the specimen at temperatures of 22°C and 50°C. It can be seen that the room temperature results show that flow into the base and out of the top are nearly equal and the slope of best-fit line is equal to 1.0023. The tests at 50°C also present a linear response with a slope of 1.0055, but for some unknown reason there is a jump of about 0.675 ml in the volume of water flowing into the base after 200 minutes. A similar jump was also observed in other steps of the test at 50°C but at different times (cumulative flows). The variations in the incremental slope of the flow line in Figure 4.55 with time are demonstrated in Figure 4.56. It can be seen that the slopes at 22°C and 50°C have both levelled off and equilibrium appears to have been reached. The jump happens at nearly 200 minutes after application of pressure gradient. In other stages this occurred at 230 and 295 minutes.

As the number of tests was limited, it was not possible to identify the cause of such a phenomenon but it is clear that it has not been caused by elevated temperature as the flow nicely continues with a nearly constant slope after the jump in the flow.

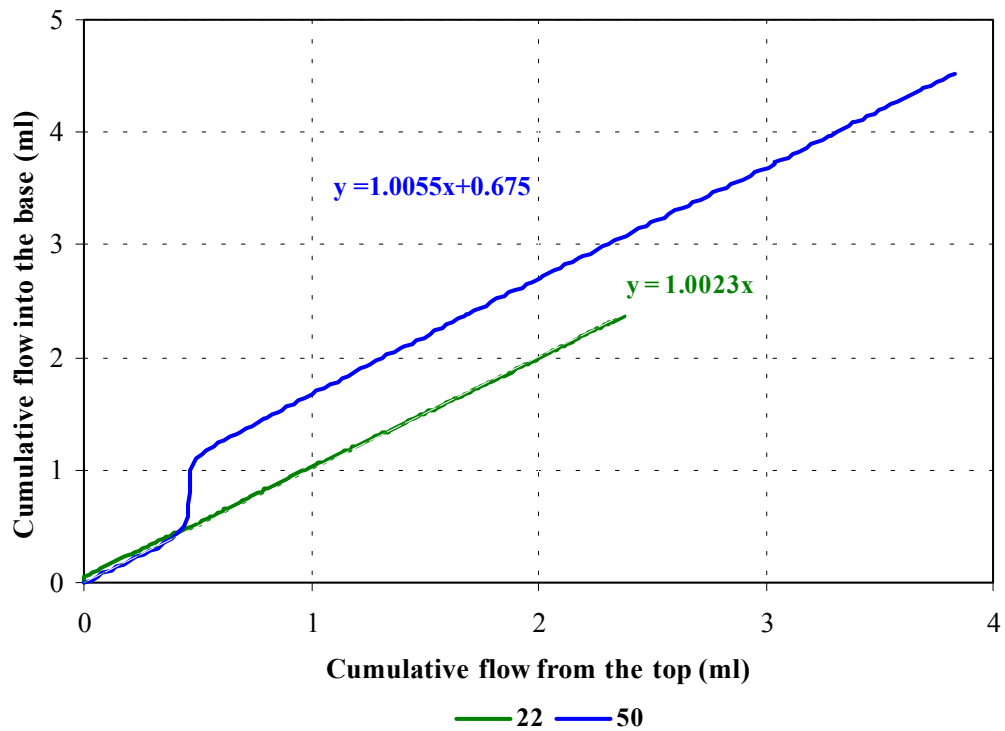


Fig 4.55 Cumulative flow of water during permeability test on M44 Clay

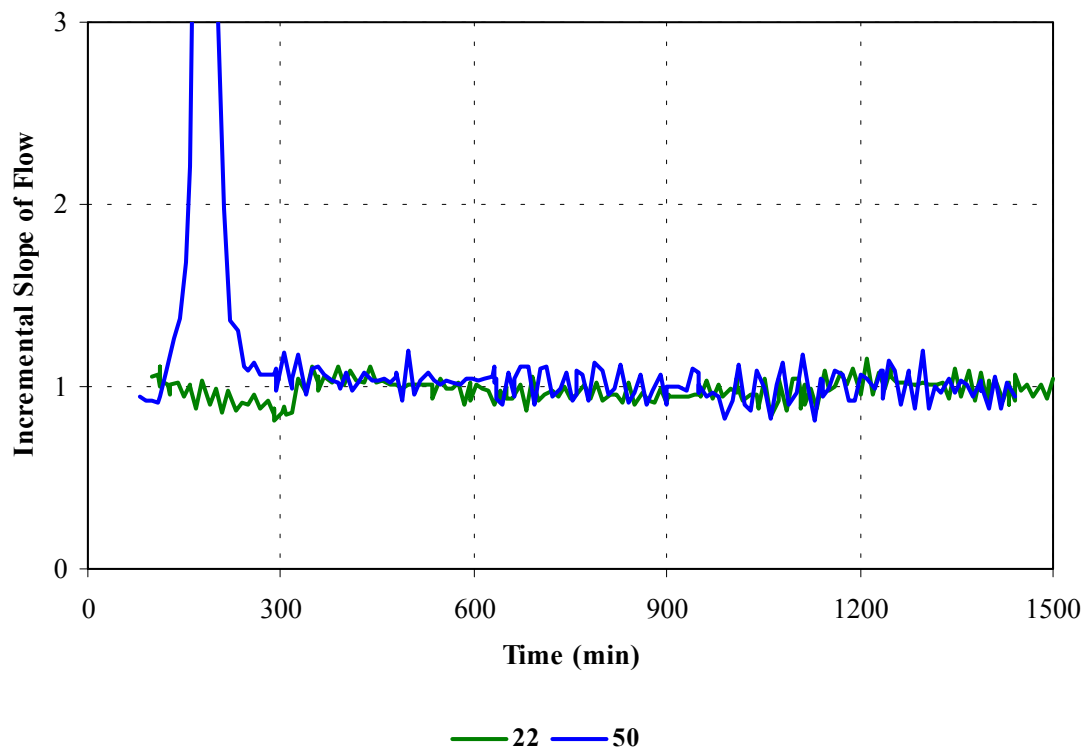


Figure 4.56 Variations in the slope of flow line with time

The values of permeability (k) were calculated using the ASTM D5084-90 method and they were corrected for the variations in the viscosity (μ_w) of water at elevated temperature. The results are summarized in the Table 4.8. The Table shows the values of permeability versus specific volume at 3 different effective stresses and at two temperatures, 22°C and 50°C.

Table 4.8 The results of direct permeability tests on M44 clay

Effective Stress (kPa)	22°C		50°C		
	k ($\times 10^{-10}$ m/s)	v	k ($\times 10^{-10}$ m/s)	$k_{\text{corrected}}$ ($\times 10^{-10}$ m/s)	v
200	3.502	1.9906	5.584	3.198	1.9801
300	2.641	1.9278	4.57	2.618	1.9169
400	1.991	1.8724	3.53	2.022	1.8612

Fig 4.57 compares the changes in permeability with changes in specific volume and temperatures.

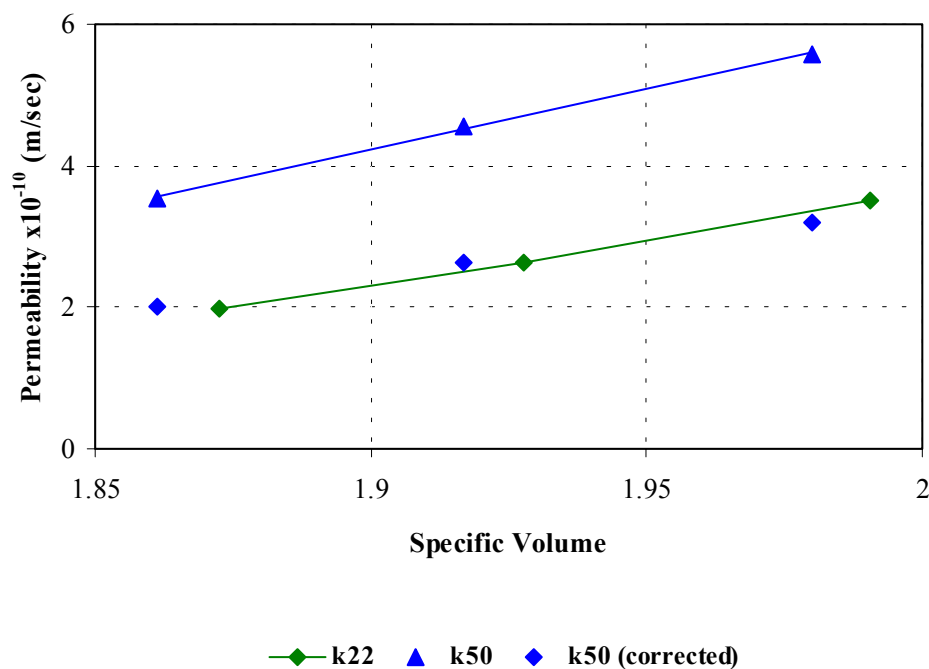


Fig 4.57 Changes of permeability with specific volume and temperature

It can be seen that the permeability at room temperature in the range of tested effective stresses increases linearly with an increase in specific volume. The sample at 50°C demonstrates higher permeability but it can be noticed that after allowance for changes in μ_w its values are clearly aligning with those at room temperature. This is in agreement with the findings of other researchers such as Habibagahi (1977) from indirect calculation of permeability using consolidation charts at different temperatures, and Delage et al (2000) from constant head permeability tests on samples of Boom clay at temperatures between 20°C and 100°C.

The coefficient of consolidation, C_v , was determined from the value of t_{90} ; the time to reach 90% consolidation, using the following relationship:

$$C_v = \frac{0.848 \times H_{dr}^2}{t_{90}} \quad (4.29)$$

H_{dr} is the length of drainage path, which in the case of drainage from both ends is the height of the specimen divided by two. Two ways drainage was used during the direct permeability tests, and Figure 4.58 shows a typical consolidation curve.

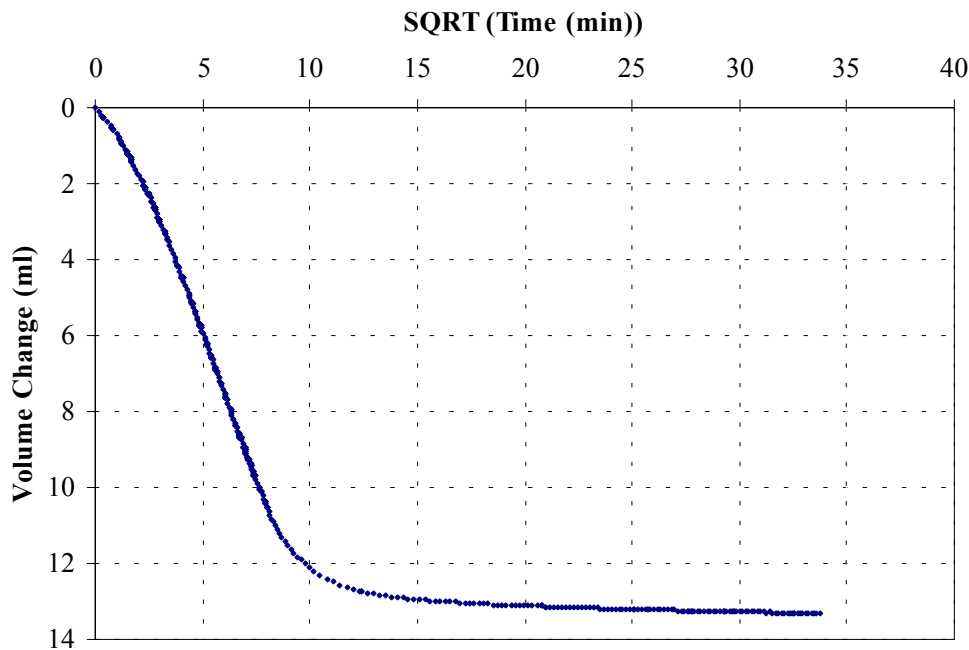


Figure 4.58 Isotropic mechanical consolidation of M44 clay

As it is shown in the graph, the time for 90% consolidation is about 100 minutes and the effective stress has been increased in one step from 80 to 200 kPa. The value of C_v from the consolidation curve and t_{90} has been calculated $5.5 \text{ mm}^2/\text{min}$. This is twice the value of $2.85 \text{ mm}^2/\text{min}$ calculated from direct permeability test; care must be taken when using the consolidation curve to determine C_v as it could over estimate the result. In the majority of triaxial tests, one end and radial drainage were used. It was noticed during consolidation, that the time for consolidation was quite dependent on the performance of the radial filter strips, which varied with the effective stress level. As a result C_v could not be reliably estimated from the consolidation response. Comparison between the results from direct and indirect calculation of permeability at 50°C shows that the value of permeability determined indirectly from the coefficient of consolidation is over estimated by a factor of approximately two. A similar observation was reported by Delage et al (2000) for another reconstituted soil.

4.4 Conclusions

The effects of temperature on aspects of the soil behaviour can be described as follows:

4.4.1 Thermo-Mechanical consolidation

- The slope of the mechanical swelling line, κ , is dependant on the effective stress and may only be considered linear for a small range. κ is also temperature dependant and has an inverse relationship with temperature.
- Heating under drained conditions causes a reduction in the volume of NC samples and thermally consolidates them. The relationship between specific volume, v , and temperature in the v - T plane is approximately linear. Deformation of NC samples during drained heating is mainly plastic and not recoverable upon cooling. The relationship between specific volume and temperature under thermal unloading-reloading (cooling-reheating) condition is almost linear. In other words, there are thermal swelling lines associated with different temperatures. Any deformation of a clay sample on these lines would be purely elastic, analogous to mechanical swelling lines. The thermal unloading-reloading lines of normally consolidated and lightly over consolidated samples are essentially parallel in the v - T plane presenting a constant slope, which is related to the coefficient of thermal expansion of the solid particles.

- Coefficients of thermal expansion of clay particles determined from the internal measurements during undrained heating are in good agreement with the reported value of 3.5×10^{-5} reported by Campanella and Mitchell (1968). Also α_s determined from drained reheating-cooling cycles appears to be reasonably close to the reported value.
- Heating under undrained conditions induces an increase in the pore pressure of NC and OC samples and consequently reduces the effective stresses. The cyclic undrained heating and cooling of M44 clay clearly demonstrates that the variations of v with effective stress are not linear in the v - p' plane. A small residual pore pressure develops in the initial cycle, but in subsequent cycles the response approaches an identical hysteresis loop.
- During an undrained thermal cycle the relationship between v and T is not linear but is quite repeatable. This relationship is the same for both NC and OC samples indicating that during undrained heating thermal volume changes are mainly direct results of thermal expansion of water and clay particles.
- The reported hysteresis loop in pore pressure was not observed in the displacement changes with temperature during undrained cycles. As this hysteresis loop was also observed during calibration of the drainage system, it might be related to the properties of water alone such as heat capacity and thermal conductivity which are known to change with temperature.
- The thermal volumetric changes determined from the internal LVDTs are slightly higher than those measured by the GDS.
- There is a series of INCLs in the v - p' plane for various temperatures with a unique slope, λ , and different N values.
- The coefficient of secondary consolidation appears to be unaffected by temperature variations for both M44 clay and Kaolin C1C.

4.4.2 Strength and Ductility

- Considering the previous and present experiments on Kaolin C1C, the shear strength during an isotropic drained triaxial test on NC samples is more likely to increase with temperature while the ductility reduces.

- The undrained shear strength of NC samples of M44 clay slightly reduces with elevated temperature irrespective of the thermo-mechanical consolidation path. In the same way, increase in temperature reduces the undrained shear strength of lightly over consolidated specimens (same OCR and p'_c) but by a greater amount. Their shear strength is also independent from the order of thermo-mechanical consolidation history. On the other hand, for the samples with higher OCR (7) the different sequences of thermal and mechanical consolidation affect the maximum undrained shear strength.

4.4.3 Stiffness

- The initial normalized shear modulus at small strains, G/p'_c , is clearly reducing with increase in temperature during drained and undrained triaxial shear tests on NC samples of M44 clay, while there is no significant change in the initial stiffness of OC samples (same OCR and p'_c).
- The overall pattern of normalized secant modulus at 50% shear strain, G_{50}/p'_c , for normally consolidated samples shows that G_{50}/p'_c decreases with increase in temperature during undrained shear tests but remains unchanged for drained shear tests.

4.4.4 Critical state

- The slope of the critical state line in the q - p' plane, M , reduces with temperature rise and its trace in the v - p' plane is shifted down.
- For all temperatures the CSL is parallel to the INCL (same λ) in the v - p' plane, and the separation between these lines slightly reduces with heating.

4.4.5 Permeability

- The result from direct permeability tests on M44 clay at temperatures up to 50°C shows firstly that the soil's permeability increases with any increase in temperature because of the reduction in the viscosity of water. Secondly, the relationship between permeability and specific volume is linear, and finally the method of indirect calculation of permeability and coefficient of consolidation from a consolidation curve overestimates the result by a factor of approximately two.

APPENDIX

4.A

Implementation of Radial Drainage

As mentioned in chapter 3 the copper top drainage line used in the original HTTA was removed in order to eliminate the associated problems with its stiffness and consequently it was decided to employ radial drainage to accelerate consolidation. Some isotropic consolidation tests on Kaolin C1C were carried out to investigate the effectiveness of radial drainage. The preparation of filter strips was according to the method provided by Head (1986). 4 strips of filter paper each 9.5 mm wide were cut from Whatman No.1 and No.54 filter papers. The strips were placed on the periphery of a sample at an angle of about 52 degrees to the horizontal and covered about 31% of the specimen periphery. It has been reported that this arrangement does not affect the measured strength of soil (e.g. Germaine and Ladd, 1988). Figure 4.A.1 shows the variations of volume change of samples of Kaolin C1C with time during consolidation at room temperature for different types of drainage.

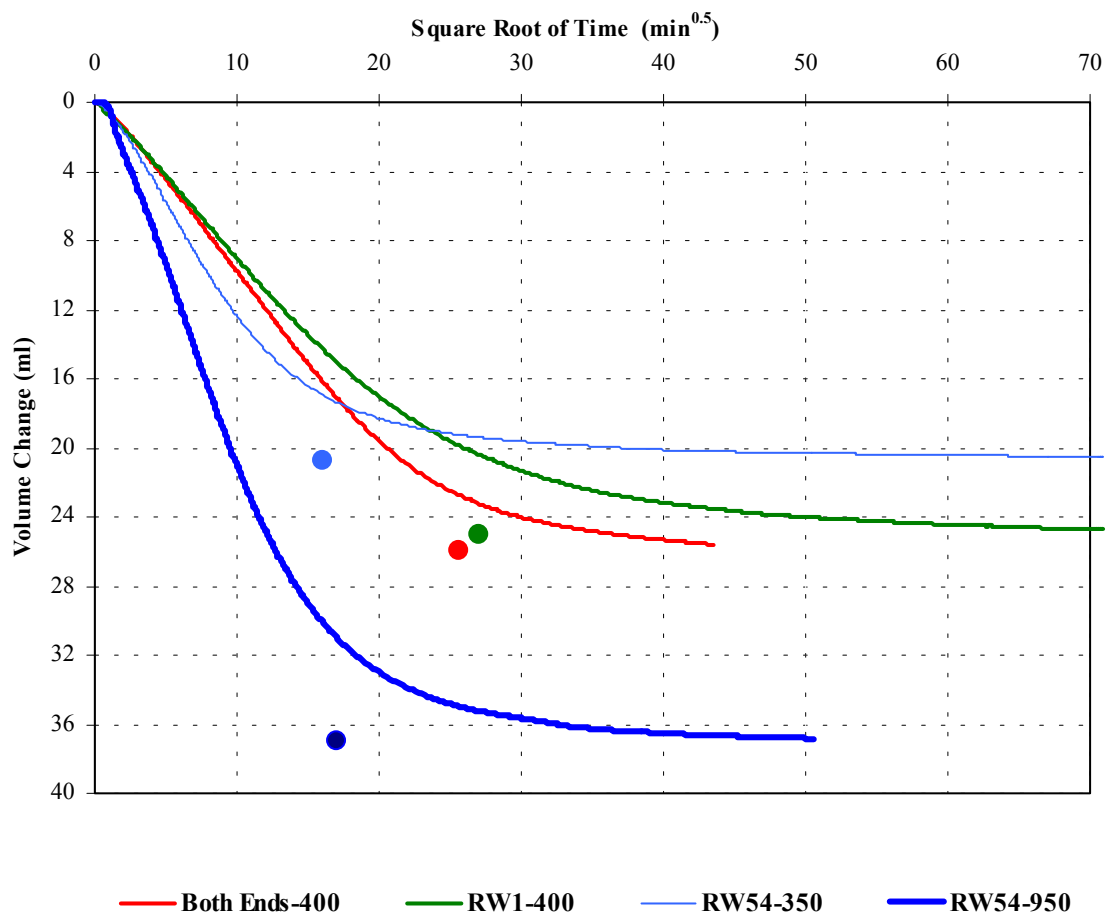


Figure 4.A.1 Changes in the volume of samples with time during consolidation

In the graph's legend the first part before dash represents the drainage type which is either from both ends or from one end with radial strips (RW1 and RW54 indicate radial strips were made from Whatman No.1 and No.54 filter papers respectively). The number after dash shows the effective stress during consolidation. The values of time for 100% consolidation, t_{100} , were determined by drawing a line through the initial linear part and a horizontal line passing through the end of each consolidation curve (Head, 1986). The time at the intersection of these two lines is considered to be t_{100} and is plotted with colours similar to each curve. As can be seen the test with radial strips made from Whatman No.1 paper presents the highest t_{100} (734 min) followed by tests with both ends drainage ($t_{100}=660$ min) and those with radial strips made from Whatman No.54 ($t_{100}=289$ and 256 min). It is clear that Whatman No.1 is not a suitable filter paper for radial drainage. It can be noticed that the shortest time for completion of consolidation is 256 min (RW54), which represents a reduction factor of about 2.6 from the consolidation time when drainage from both ends was used. This is much less than the theoretical factor of 5 to 10 suggested by Bishop and Henkel (1962).

Determination of Loading Rate

The rate of loading during triaxial shear tests must be slow enough to allow the equilibrium of pore pressure within the sample during undrained tests and the dissipation of pore water during drained tests. It has been reported that a fast rate of loading causes an ill estimation of shear strength while a rate slower than needed has an insignificant effect on the estimated shear strength (Bishop and Henkel, 1962). The rates of loading during drained and undrained tests have been calculated using the reported method by Head (1986) and the time for failure, t_f , as follows:

$$\text{Drained:} \quad t_f = 14.2t_{100}$$

$$\text{Undrained:} \quad t_f = 1.59t_{100}$$

The above equations are valid when the ratio of height to diameter is 2 and drainage is radial and from one end. The value of t_{100} has been determined for M44 clay to be between 260 and 324 minutes using a consolidation curve similar to Kaolin C1C (see Figure 4.A.1). Considering the upper limit of $t_{100}=324$ min, the times for failure are calculated to be 515 and 4600 minutes during undrained and drained tests respectively. Assuming 10% axial strain for undrained and 20% for drained tests to reach the failure

state the loading rate will be about 0.02 (undrained) and 0.004 mm/min (drained) considering a 100mm-height sample. As t_{100} was found to be dependent on the efficiency of filter strips it was decided to use slower rates of 0.01 and 0.002 mm/min for undrained and drained tests respectively.

APPENDIX

4.B

Results from consolidation of M44 clay

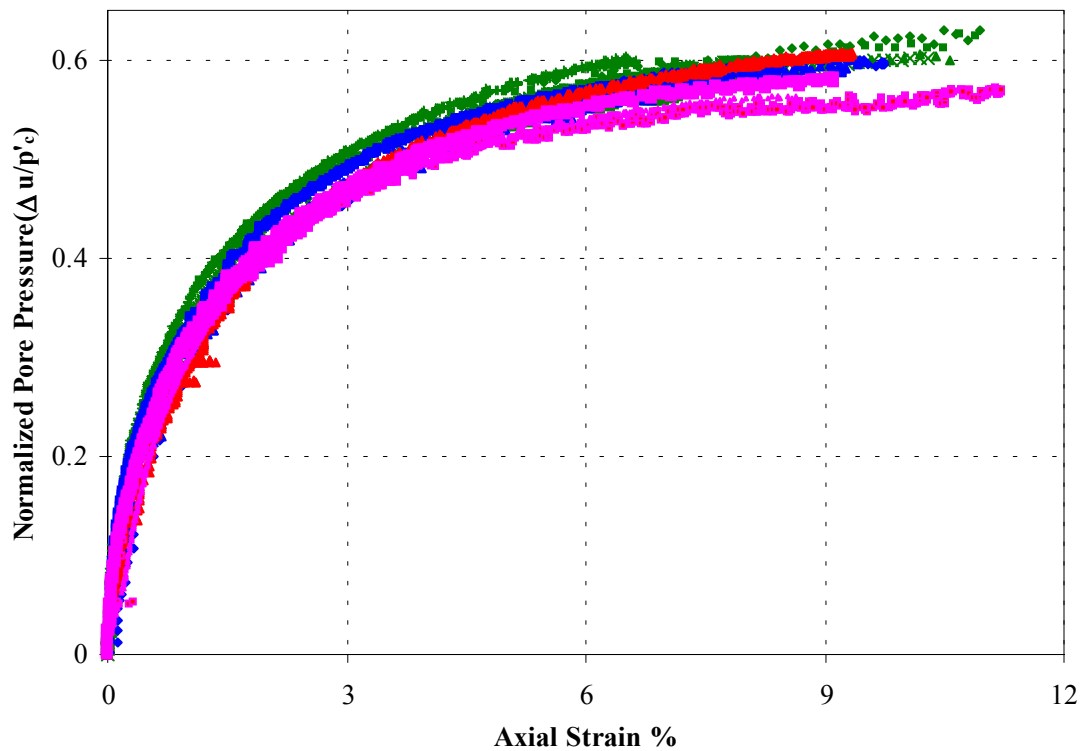
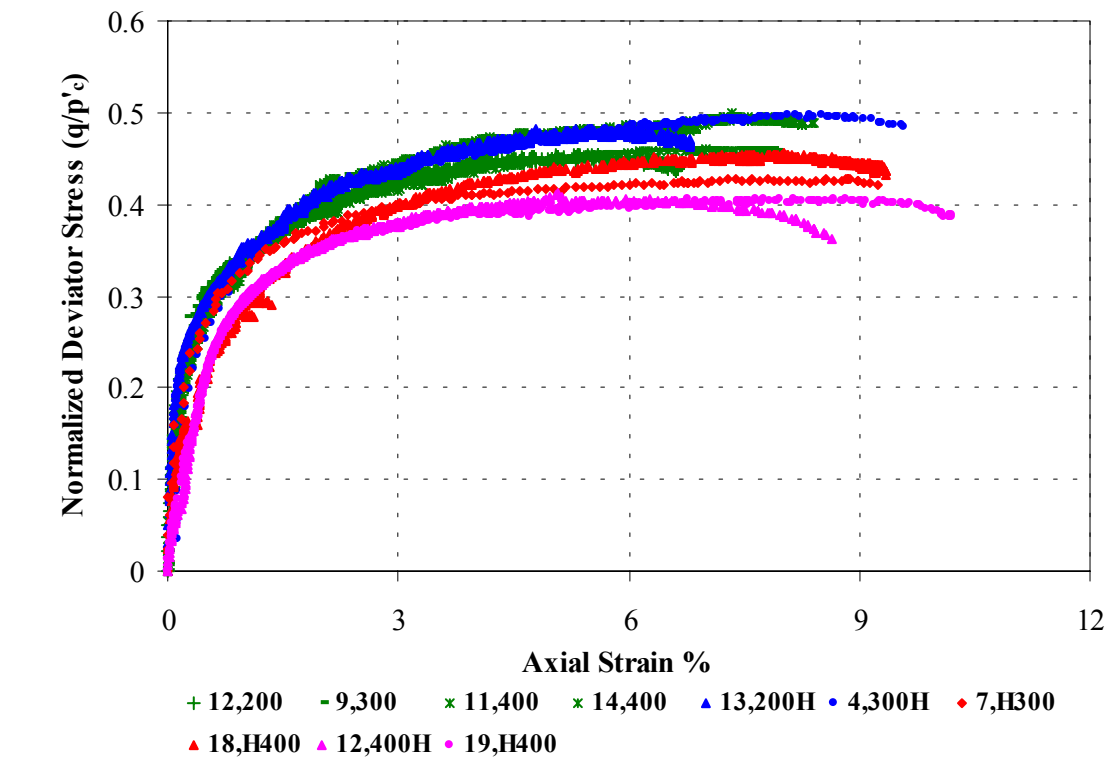
Sample No.	p'_c (kPa)	v_c				Comments
		22°C	50°C	75°C	100°C	
RTUN1	150	2.0343				
	350	1.881				
	550	1.7985				
RTUN2	350	1.8607				
RTUN3	150	2.0039				
RTUO4	550	1.6809				
	50	1.8011				
RTUN5	150	2.0193				
RTDN6	250	1.9339				
RTDN7	450	1.8458				
RTUO8	650	1.7569				
	50	1.8665				
RTUN9	300	1.9371				
RTDN10	400	1.8506				
RTUN11	400	1.8507				
RTUN12	200	1.981				
RTUN13	400	1.8665				
RTUN14	400	1.8627				
RTUO15	500	1.8246				
	200	1.8586				
HTUN2	300	1.9004	1.8839			
HTUN3	400	1.8653	1.8428			
HTUN4	300	1.8990	1.8796			
HTDN5	400	1.8879		1.8585		
HTDN6	200	1.9951	1.9767	1.9554		Path A
HTUN7	80	2.1377	2.1238	2.1123		Path A
HTUN7	300			1.8787		Path A
HTUN8	200	1.9423			1.9061	Path C
	128		1.9520			
	93			1.9654		
	59				1.9831	
	200					
HTUN9	400	1.8355		1.8147	1.8005	Path A, Sample slightly disturbed
HTDN10	300	1.8959	1.8804	1.8591	1.8423	Path A
HTDN11	300	1.9010	1.8894	1.8789	1.8615	Path A
HTUN12	400	1.8464	1.8332	1.8227	1.8081	Path A
HTUN13	200	1.9779	1.9604			Path A
HTUO14	700	1.7653				Path E
	100	1.8502	1.8622	1.8625	1.8600	
HTUO15	80	2.2049	2.1933	2.1841	2.1635	Path F
	700				1.7228	
	100				1.8246	
HTUO16	400	1.8649				Path G
	261		1.8737			
	174			1.8863		
	118				1.9036	
	346	1.8667				
	246		1.8736			
	165			1.8862		
	100				1.9032	
	341	1.8661				
	400	1.8536				
	500	1.8171				
	200	1.8527				
	150		1.8616			

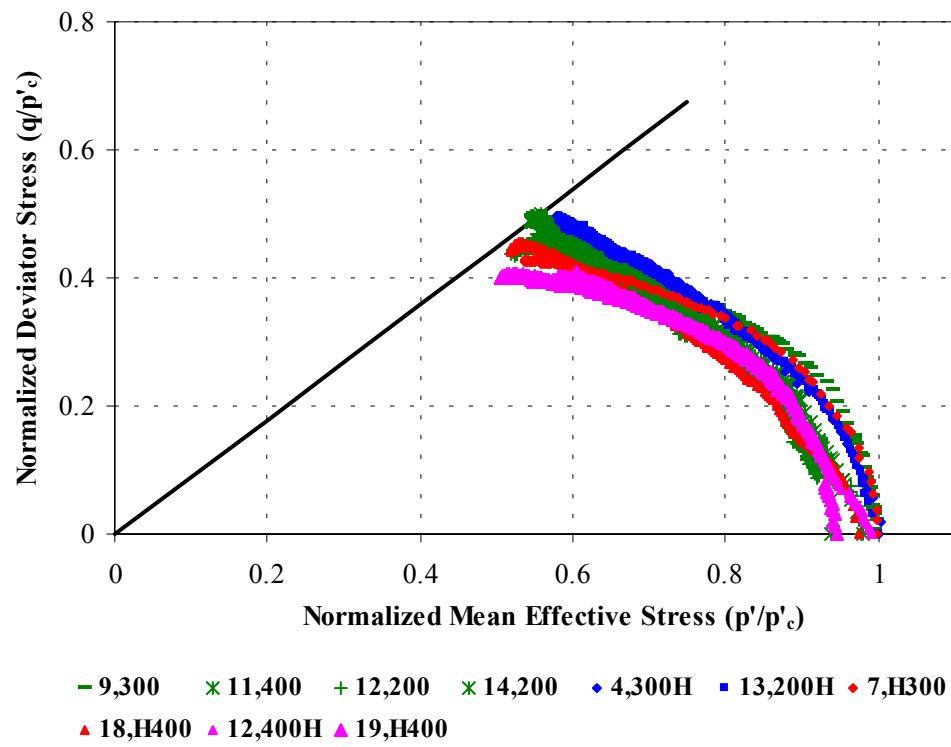
Sample No.	p'_c (kPa)	v_c				Comments
		22°C	50°C	75°C	100°C	
	101			1.8743		
	70				1.8926	
	262	1.8539				
	181		1.8619			
	119			1.8741		
	72.4				1.8919	
	200				1.8546	
HTUO17	400	1.8627	1.8511	1.8366	1.8177	Path H
		1.8231	1.8224	1.8206		
			1.8219	1.8198	1.8160	
	400	1.8203				
	500	1.8153				
	200	1.8385	1.8391	1.8386	1.8376	
	200	1.8438				
	200		1.8428	1.8405	1.8382	
HTUN18	80	2.1632		2.1387		Path B
	400			1.8641		
HTUN19	80	2.1475	2.1383		2.1098	Path B
	400				1.8376	
HTDN20	80	2.2080	2.1944	2.1780		Path B
	400			1.8817		

The letters in the sample number are in order from left to right: temperature status (RT for room and HT for high temperature), drainage condition (D or U), consolidation status (N for normally and O for over consolidated), and the final characters are the test number.

APPENDIX

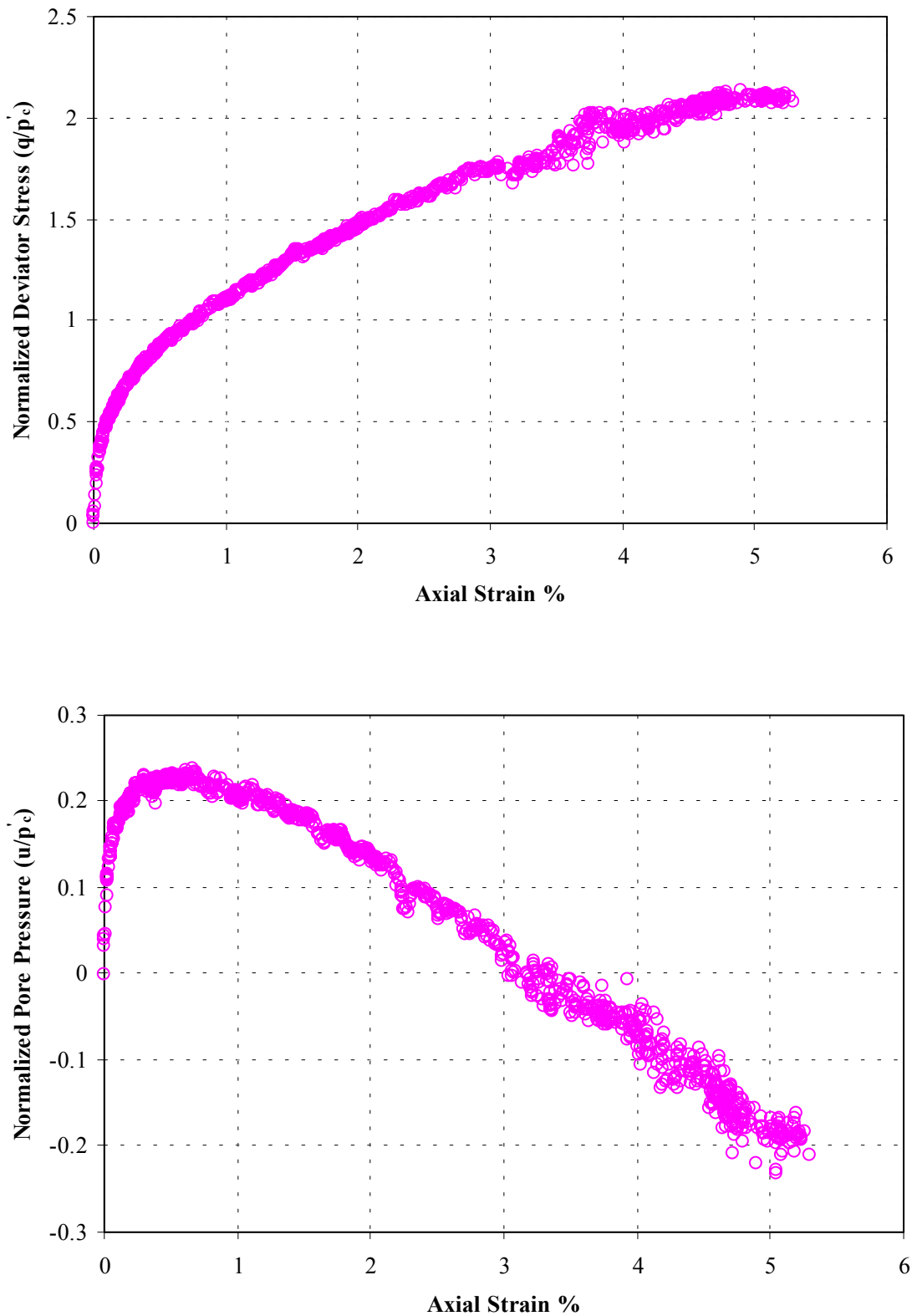
4.C

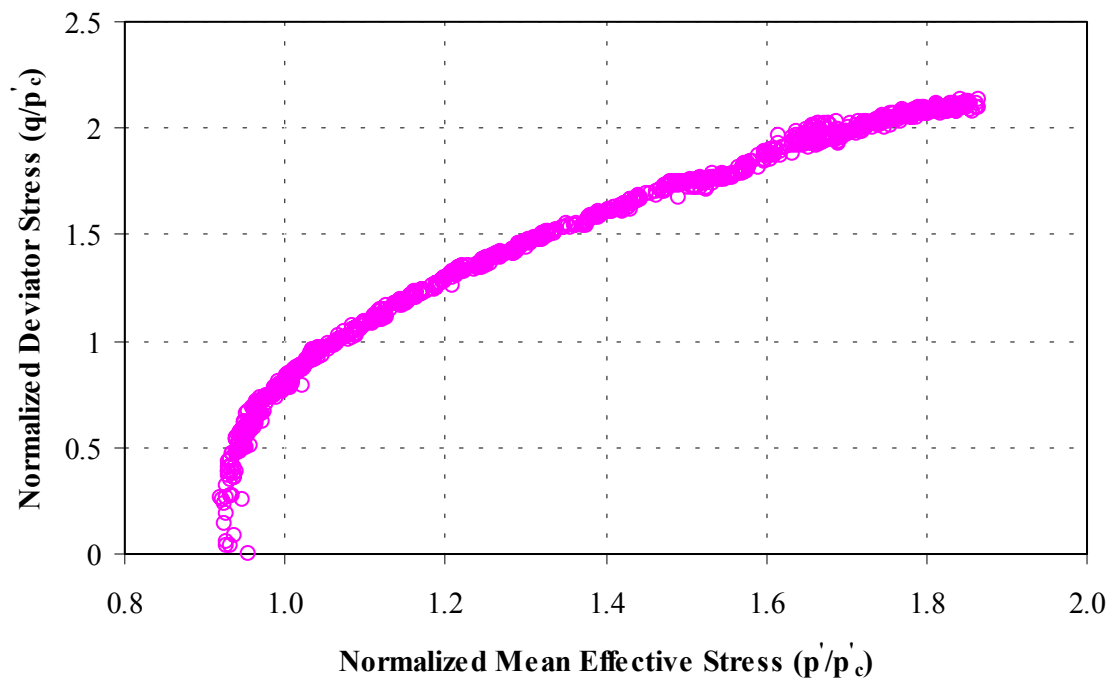
Results from undrained shear tests on M44 clay (— 22°C, — 50°C, — 75°C, — 100°C)

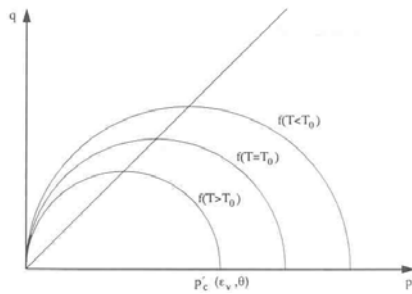


APPENDIX *4.D*

Results from undrained shear tests on sample HTUO2







CHAPTER

5

THERMO-MECHANICAL MODELS FOR SOIL

5.1 Introduction

A number of models of soil behaviour at elevated temperature have been described in the literature. They are mainly based on the framework of critical state soil mechanics and the Cam clay model. The Cam clay model referred to here is the modified Cam clay, which was originally described by Roscoe and Burland (1968). The Cam clay model has been widely used for clay by many geotechnical experts due to its simplicity and because all parameters needed for modelling can easily be obtained through conventional triaxial tests in the laboratory. It has been shown by Wood (1990) that the differences between this model and other more complicated models are not significant at room temperature. In order to simulate the complex thermo-mechanical behaviour of soil there has been a tendency to increase the number of physically meaningless parameters by introducing curve fitting approaches to describe the thermal effects. The experimental results describing the thermo-mechanical behaviour of M44 clay were thoroughly discussed in the previous chapter. In this chapter the applicability of some of the soil models are investigated by comparing their predictions with the experimental results of M44 clay. The thermo elasto-plastic model of Cui et al (2000) will be the centre of discussion. For the purpose of comparison their approach is implemented to predict the volumetric changes due to heating. The Cam clay model is used to simulate the stress-strain response of M44 clay during shearing. Finally the shortcomings of the models are discussed and suggestions are made for future research and development of a new model.

5.2 Background on Thermo-Elastic-Plastic models for clay

As discussed in chapter 2 there have been many attempts to derive models for soil behaviour at elevated temperature since 1960. Heating under drained conditions can contract or expand saturated soils, known as thermal consolidation, while undrained heating increases the pore pressure. Campanella and Mitchell (1968) investigated thermally induced pore pressure and volume changes and proposed mathematical solutions to these phenomena. The proposed model by Campanella and Mitchell has been examined by many researchers (e.g. Moritz 1995) and reported to have reasonable agreement with experimental data. Campanella and Mitchell's method was not examined in this thesis because firstly determination of the swelling index (κ) depends on the state of effective stress and OCR. Secondly the assumption that the pore water behaves like free water may not be applicable in the range of 18°C to 60°C (temperature range in their experiment) although it might be applied at temperatures higher than 70°C (Derjaguin 1986). Thirdly, this approach cannot predict the behaviour of soil under deviatoric conditions. Finally, further experimental works by Baldi et al (1988) have shown that the thermal contractions of normally consolidated (NC) clays are gradually converted to expansion at higher OCRs. The experimental results on M44 clay confirmed this phenomenon. Baldi et al also showed that the assumption of free water made by Campanella and Mitchell (1968) was not applicable for low porosity Pontida silty clay. Hueckel and Baldi (1990) proposed a numerical approach that included the effects of OCR. This model has not been implemented because new findings, such as the thermal over consolidation effects reported by Towhata et al (1993), have not been included in their model, and because this model needs a number of parameters which are not possible to determine through triaxial tests. Instead a more sophisticated model presented by Cui et al (2000) based on the same fundamentals of Hueckel and Baldi's approach is used for simulation of M44 clay response to heating for several reasons:

- It is one of the latest developed models (Cui et al 2000) and it seems to be the most complete.
- It has been claimed to clearly indicate the expansion contraction behaviour of over consolidated clays at high OCRs.
- It can predict the thermal over consolidation effects reported by Towhata et al (1993).

- In association with the Cam clay model it can predict the stress-strain response of soil to deviatoric loading.

Seneviratne et al (1993) critically examined the models proposed by Britto et al (1989) and Hueckel and Borsetto (1990). They showed that in the range of normally consolidated and lightly over consolidated samples both models provided reasonable predictions under isotropic stress conditions. Seneviratne et al's model assumed that the compression index, λ , and swelling index, κ , are independent of temperature and only a shift in the normal consolidation line (NCL) and critical state line (CSL) occurs with increase in temperature. Also the shape of yield locus remains unaffected with temperature changes and only shifts to account for NCL movements. The findings of this study confirmed shifts in the INCL and CSL due to temperature changes, but showed κ and M (slope of CSL in q - p' plane) were not constant and slightly reduced with heating. Similar to Campanella and Mitchell's approach, Seneviratne et al's model also cannot predict thermally induced expansion-contraction behaviour at high OCRs and only can be used for NC and lightly OC soils. The only advantage of Seneviratne et al's model is the simplicity as it has only one extra variable to Cam clay model which is β , the coefficient of effective thermal volume expansion (Seneviratne et al 1993). Tanaka et al (1996, 1997) and Graham et al (2001) developed a thermo elastic-plastic model with some modifications to the Cam clay model. They have experimentally confirmed the findings of Hueckel and Baldi (1990) regarding changes in the size of the yield locus with temperature. In contrast to the experimental results in this thesis, they assumed that κ increases with increase in temperature. This assumption was made to cover the dependency of volumetric strain to OCR. Also their model indicates that the undrained shear strength increases due to heating although their experimental data showed the opposite trend. As has been mentioned earlier in chapter 2, the key assumption of nearly all recently developed models, the expansion contraction behaviour observed at higher OCRs, may not be always true. Burghignoli et al (2000) claimed that the recent stress history of soil plays a major role as NC and OC samples with a recent stress history of loading or reloading indicate volume contraction upon heating even at high OCRs. To the author's knowledge there has not been any new development in the modelling of soil to include such a phenomenon. In consequence, despite

many shortcomings Cui et al's (2000) model is implemented for the purpose of comparison with the experimental results on M44 clay considering the closeness of their assumptions to the findings of experiments on M44 clay and other experimental data reported in the literature. It is intended to investigate the effectiveness of the complexity in Cui et al's model and also to show where the current state of research on thermo-mechanical behaviour of soil stands.

5.3 Implementation of Thermo-Mechanical Models

Cui et al's model has been used for predictions of soil behaviour during isotropic thermo-mechanical consolidation but the Cam clay model and the critical state framework have been employed for predictions of triaxial stress states (deviatoric loading).

5.3.1 The Elastoplastic model proposed by Cui et al (2000)

The proposed model provides a new volumetric thermal plastic mechanism for predictions of plastic strains at higher OCRs and over consolidation effects due to heating. This model has some additions to the extended Cam clay model proposed by Hueckel and Baldi (1990) and is based on the following assumptions:

- λ , the slope of the NCL, is independent of temperature and preconsolidation pressure decreases due to heating.
- Heating may cause over consolidation in NC samples under constant load.
- The plastic contraction of NC samples due to heating is gradually converted to expansion at higher OCRs.
- The applied load has no effect on the irreversible thermally induced volume changes of normally consolidated (NC) samples.
- The slope of unloading line, κ , and the critical state parameter M are constants and independent of temperature.

The slight changes in κ observed in the previous chapter have been ignored to comply with the assumptions of this model but M has been considered to be dependent on temperature. The non-linear reduction in preconsolidation pressure induced by heating (Erickson 1989) was used by Hueckel and Baldi (1990) to define a yield locus in T - p'

space. As can be seen in Figure 5.1, any changes in stress or temperature on the left side of the T - p' yield locus cause recoverable strains. In contrast when the yield locus is reached plastic strain occurs and the yield locus is shifted to the right increasing the elastic zone. This mechanism can predict the thermal contractions of normally consolidated samples due to heating but it is not capable of predicting the expansion contraction behaviour of over consolidated samples reported by Baldi et al (1991) and just predicts elastic thermal strains.

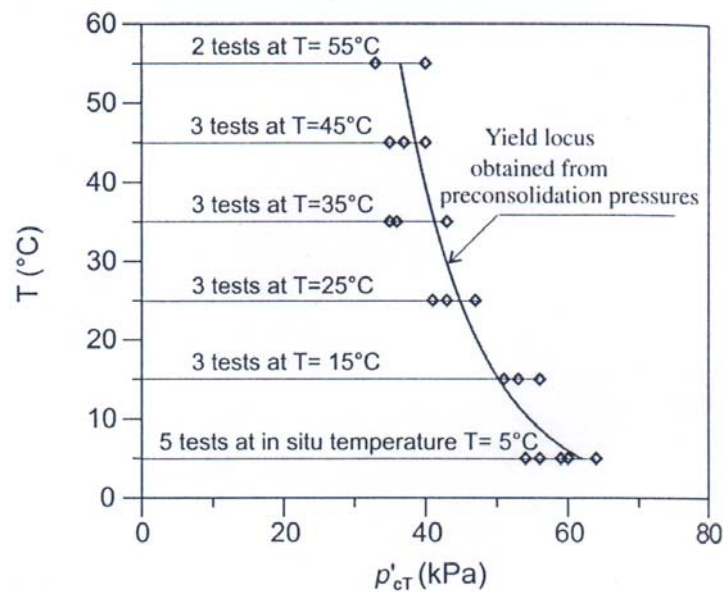
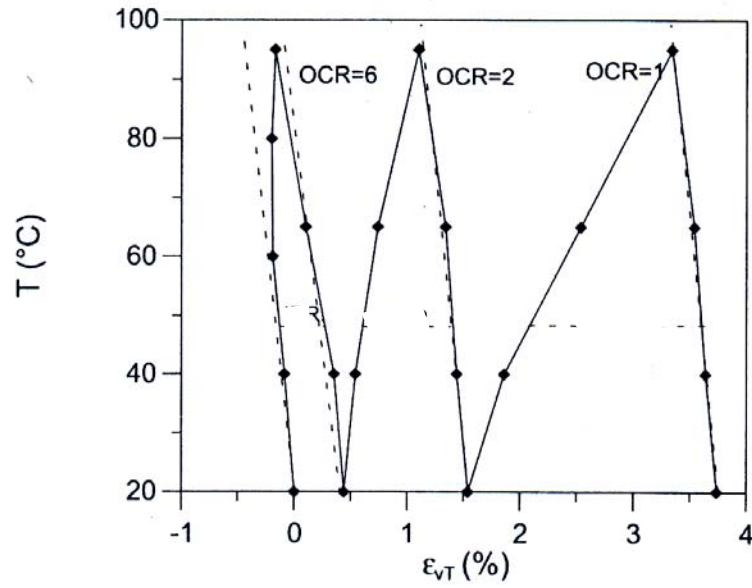


Figure 5.1 Changes in the preconsolidation pressure with temperature (after Eriksson 1989)

Figure 5.2 (after Baldi et al 1991) shows that at $OCR = 2$ and $OCR = 1$ the sample contracts during heating to 90°C and contracts when it is cooled down but for $OCR = 6$ the sample responds differently to heating. It initially expands up to 60°C then contracts. In consequence Cui et al (2000) added a new plastic mechanism to cover the above phenomenon.



5.2 Thermal volumetric strains of a sample of Boom clay at three OCRs (After Baldi et al 1991)

The reversible thermal strain under drained conditions has been proposed to obey the following equation:

$$d\varepsilon_v^e = \alpha_2 dT + \frac{\kappa}{v} \frac{dp'}{p'} \quad (5.1)$$

Parameter α_2 is the thermal expansion coefficient of the drained soil and is used for calculation of elastic thermal strain. As was mentioned earlier, κ is considered temperature independent here in contrast with the findings of Campanella and Mitchell (1968) and Despax (1976) who showed slight reductions in κ with temperature. Also the experimental results in chapter 4 demonstrated a similar pattern. If κ reduces with temperature the elastic volumetric strain will reduce at higher temperature.

For the first volumetric mechanism Cui et al fitted an exponential expression for the LY (loading yield) locus in Figure 5.1 as follows:

$$p'_{cT} = p'_{c_0} \exp(-\alpha_0 \Delta T) \quad (5.2)$$

As it is shown in Figure 5.3, the preconsolidation pressure p'_{c_0} is defined by the intersection of LY with the p' axis. p'_{c_0} is a hardening parameter. α_0 defines the curvature of LY.

The second volumetric plastic mechanism is defined with the second yield locus called thermal yield (TY), which is activated by heating in the range of higher OCRs. If the sample is heated up to a temperature higher than the maximum temperature that has ever been supported by the soil it will lead to a plastic strain. Consequently the initial shape of the TY curve must be very close to the p' axis and is represented by an exponential function considering the p' axis as an asymptote. It should be noted that the derivation of the TY locus was only based on the experimental results of Baldi et al (1991) shown in Figure 5.2 and does not have a sound experimental basis. The equation of the TY yield locus is as follows:

$$T_{CT} = (T_C - T_0) \exp(-\beta p') + T_0 \quad (5.3)$$

T_C is a reference temperature corresponding to the intersection of TY curves with the T axis. As it is shown in Figure 5.4, β is a hardening parameter that defines the curvature of the yield locus TY and ranges from 0.4 to 800 according to Cui et al. Under the TY yield locus any changes in temperature or mean effective stress cause only elastic strains. Any thermo-mechanical path crossing TY will generate thermal plastic strain and reduce the hardening parameter β while T_C remains constant.

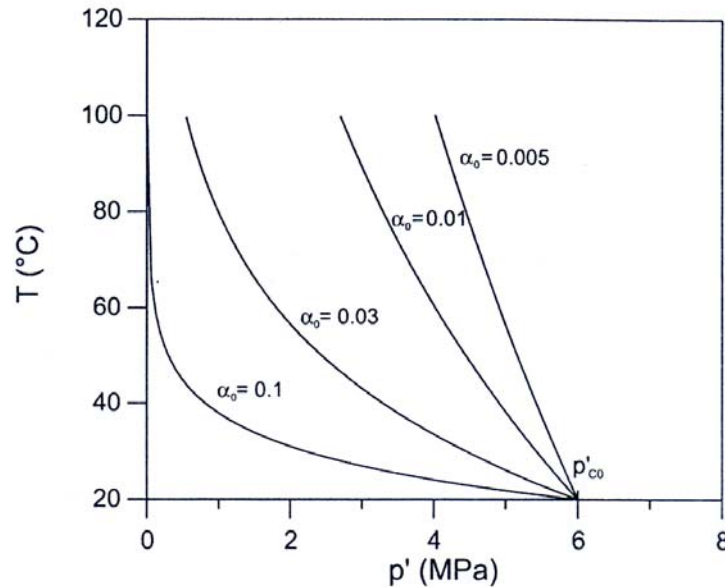


Figure 5.3 The LY Yield curves (After Cui et al 2000)

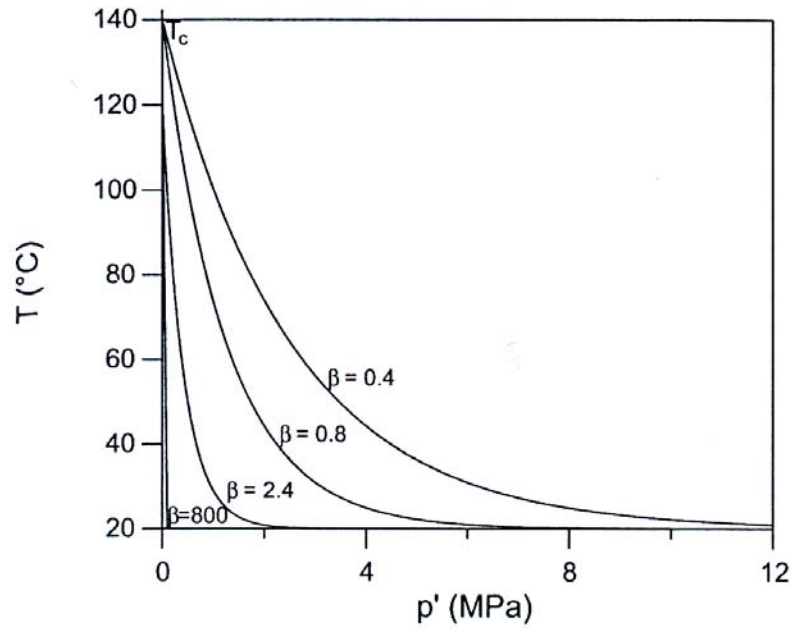


Figure 5.4 Variations of TY curves with changes in β (after Cui et al 2000)

Cui et al have also defined another locus to implement the transition between expansion and contraction at higher OCRs in which the higher OCR leads to a higher temperature for transition. This locus is called the HC curve and is defined by the following equation:

$$p' = C_1 p'_{C_0} \exp(C_2 \Delta T) \quad (5.4)$$

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

When the loading path crosses the LY curve the plastic volumetric strain due to mechanical loading, $d\varepsilon_{vm}^p$, can be evaluated using the following critical state equation:

$$d\varepsilon_{vm}^p = \frac{\lambda - \kappa}{v} \frac{dp'_{C_0}}{p'_{C_0}} \quad (5.5)$$

Cui et al fitted an exponential curve to the experimental data showing variations of thermo-plastic volumetric strains of Boom clay with temperature (reported by Sultan, 1997) and suggested the following expression:

$$\varepsilon_{VT}^p = \exp(\alpha_p \Delta T) - \alpha_p \Delta T - 1 \quad (5.6)$$

After derivation:

$$d\varepsilon_{VT}^p = \alpha_p [\exp(\alpha_p \Delta T) - a] dT \quad (5.7)$$

So the α_p and a are parameters related to the slope and the shape of thermal plastic strain curve respectively. α_p is constant for normally consolidated soil (Demars and Charles 1982) and independent from the applied stress. For over consolidated samples at high OCR, $OCR > 1/C_1$, there is a transition point from expansion to contraction in which the changes in thermal volumetric strain are zero and therefore:

$$d\varepsilon_{VT} = d\varepsilon_{VT}^e + d\varepsilon_{VT}^p = 0 \quad (5.8)$$

Leading to:

$$\alpha_2 + \alpha_p [\exp(\alpha_p \Delta T) - a] = 0 \quad (5.9)$$

At the intersection of the HC curve with the p' axis the value of ΔT is zero:

$$\alpha_p = \frac{-\alpha_2}{1-a} \quad (5.10)$$

Substituting 5.10 in 5.6:

$$\varepsilon_{VT}^p = \exp\left(\frac{-\alpha_2}{1-a}\right) \Delta T - a \left(\frac{-\alpha_2}{1-a}\right) \Delta T - 1 \quad (5.11)$$

For normally consolidated and lightly over consolidated samples α_p is constant so the parameter a can be easily determined from (5.11) by running heating tests on NC samples under isotropic conditions. Taking into account the fact that parameter "a" is close to unity (Cui et al 2000), it is expected from equation 5.10 that α_p would be very sensitive to variations of a .

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

$$d\varepsilon_{VTm}^p = \alpha_1 \frac{dp'}{p'} \quad (5.12)$$

Equation 5.12 is based on the thermal over consolidation effects observed by Towhata et al (1993) and Sultan (1997). In other words, if a NC sample is mechanically consolidated after thermal consolidation, the mechanical consolidation is initially

developed by a slope less than λ , i.e. $\kappa + \alpha_1$, in the v - p' plane causing a quasi-preconsolidation effect.

In the absence of experimental data Cui et al (2000) suggested that if the LY yield curve is reached at constant load due to heating, the observed thermal plastic strain $d\varepsilon_{vmT}^p$ would be similar to the plastic thermal strain on TY yield curve, $d\varepsilon_{vT}^p$.

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:

$$d\beta = \frac{-\exp(\beta p')}{p'(T_c - T_0)\alpha_p[\exp(\alpha_p \Delta T) - a]} d\varepsilon_{vT}^p - \frac{\beta}{\alpha_1} d\varepsilon_{vTm}^p \quad (5.13)$$

$$\frac{dp'_{Co}}{p'_{Co}} = \frac{\alpha_0}{\alpha_p[\exp(\alpha_p \Delta T) - a]} d\varepsilon_{vmT}^p + \frac{v}{\lambda - \kappa} d\varepsilon_{vm}^p \quad (5.14)$$

The coupling of the two mechanisms leads to:

$$\begin{aligned} \frac{dp'_{Co}}{p'_{Co}} = & \frac{\alpha_0}{\alpha_p[\exp(\alpha_p \Delta T) - a]} d\varepsilon_{vmT}^p + \frac{v}{\lambda - \kappa} (d\varepsilon_{vm}^p + d\varepsilon_{vTm}^p) + \\ & + \left\{ \frac{\alpha_0}{\alpha_p[\exp(\alpha_p \Delta T) - a]} + k_1 \left[\frac{v}{\lambda - \kappa} \right] \right\} d\varepsilon_{vT}^p \end{aligned} \quad (5.15)$$

Parameters k_1 and α_1 depend on overconsolidation effects due to heating of NC samples. As this phenomenon was not clearly identified for M44 clay it has been assumed that $k_1 = 0$ and $\alpha_1 = \lambda$.

5.3.2 Modified Cam Clay model for deviatoric loading

As has been reported in chapter 4, triaxial shearing tests were carried out only under isothermal conditions. The modified Cam clay model (Roscoe and Burland, 1968) is used here for predictions of the stress-strain response of M44 clay. The formulation of this model has been extracted from Wood (1990). The yield locus in the q - p' plane is an ellipse and is defined as:

$$f = q^2 - M^2[p'(p'_0 - p')] = 0 \quad (5.16)$$

p'_0 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:

$$\frac{d\varepsilon_v^p}{d\varepsilon_s^p} = \frac{M^2(2p' - p'_0)}{2q} \quad (5.17)$$

where $d\varepsilon_s^p$ is the increment of plastic shear strain. The elastic and plastic volumetric strains during deviatoric loading are given by equations 5.1 and 5.5 respectively. The elastic and plastic shear strains can be determined from the following expressions:

$$d\varepsilon_s^e = \frac{dq}{3G} \quad (5.18)$$

$$d\varepsilon_s^p = \frac{(\lambda - \kappa)}{vp'(M^2 + \eta^2)} \left[2\eta dp' + \frac{4\eta^2}{(M^2 - \eta^2)} dq \right] \quad (5.19)$$

Where $\eta = q/p'$ is the stress ratio. Figure 5.5 shows the elliptical yield locus for the modified Cam clay model. According to Cam clay the mean effective stress at failure, p'_{cs} , is equal to half of p'_0 . This implies that the vertical separation between the isotropic normal consolidation line (INCL) and critical state line (CSL), $N-\Gamma$, is constant and equal to $(\lambda - \kappa)\ln 2$. The experimental data on M44 clay have shown that both the INCL and CSL shift to a lower location in the $v-p'$ plane with any increase in temperature and the amount of vertical separation ($N-\Gamma$) reduces slightly with increase in temperature. Table 5.1 demonstrates the values for vertical separations of INCLs and CSLs at temperatures between 22°C and 100°C.

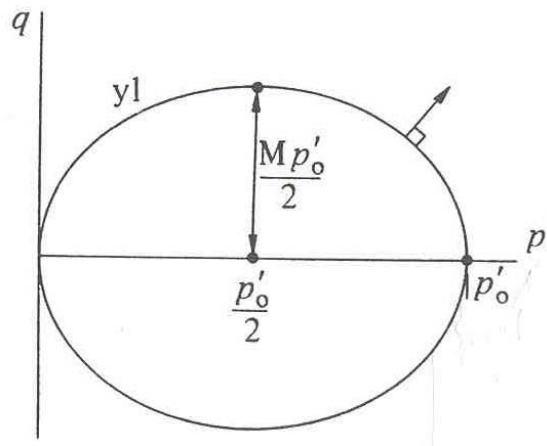


Figure 5.5 Elliptical yield locus for Cam clay (after wood 1990)

Table 5.1 Shifts and vertical separations of INCLs and CSLs

Temperature	ΔN	$\Delta \Gamma$	Temperature	$N-\Gamma$	$(\lambda-\kappa)\ln 2$
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

It can be seen in table 5.1 that the values of the shifts in INCLs and CSLs are not equal and their average shifts are 0.017 and 0.012 for every 25°C temperature increment respectively. Also it is clear that $N-\Gamma$, the vertical separations between the INCL and CSL, which is define here as the spacing ratio (SR), is different at various temperatures and is not in general equal to $(\lambda-\kappa)\ln 2$. These types of observations cannot be predicted with simple models and to the authors knowledge there have not been any major developments in the thermo-mechanical modelling of soil until now to allow for such behaviour, although it would be relatively simple to make SR a function of temperature. Seneviratne et al (1993) considered a shift in the CSL by the same amount as in the INCL indicating a constant SR. Graham et al (2001) also assumed that the CSLs would shift in $v-p'$ plane similar to those for the INCLs due to heating although their experimental results are not convincingly showing this phenomenon. For the purpose of simplicity a similar approach has been employed here. It is assumed that both INCL and CSL shift 0.017 for every 25°C increase in temperature. The values of SR ($N-\Gamma$) and $(\lambda-\kappa)\ln 2$ have been adjusted to 0.0958 by changing Γ and κ . Considering the data in Table 4.3 and Table 5.1, the values used in the modelling shown in Table 5.2 are obtained.

Table 5.2 Assumed parameters for Cam clay model

Temperature	N	N^*	Γ	Γ^*	λ	κ	κ^*	M	μ'
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

*Assumed value

5.4 Determination of parameters

In addition to the parameters cited in table 5.2 the following parameters α_0 , T_c , C_1 , C_2 , α_2 , a , k , and α_1 must be determined in order to implement Cui et al's elasto-plastic

model. Of these, as mentioned earlier, k is considered to be zero because the observed thermal overconsolidation effects on M44 clay were insignificant. α_0 defines the LY yield locus and can be determined by performing mechanical consolidation tests at two constant temperatures. Therefore, temperatures of T_0 and T will have two associated INCLs given by the following expressions:

$$v_{T_0} = N_{T_0} - \lambda \ln p'_{T_0} \quad (5.20)$$

$$v_T = N_T - \lambda \ln p'_T \quad (5.21)$$

Considering a horizontal path at constant v from p'_{T_0} to p'_T in v - p' plane leads to:

$$p'_T = p'_{T_0} \exp\left(\frac{N_T - N_{T_0}}{\lambda}\right) \quad (5.22)$$

Comparing (5.22) with (5.2) the parameter α_0 is given by:

$$\alpha_0 = \frac{N_{T_0} - N_T}{\lambda \Delta T} \quad (5.23)$$

The reference temperature, T_c , is needed to define the TY yield locus. According to Cui et al (2000), it must be determined by running two heating tests at two different mean effective stresses on one sample. The first heating-cooling cycle activates the TC yield curve. The second heating test on the same sample is carried out at a higher mean effective stress, the temperature at which the consolidation path crosses the TY yield curve is recorded. Using these values of p' and T and substituting in (5.3) the value of T_c can be calculated. In the absence of appropriate data, the value of T_c was attained using a different approach in which the second heating test was performed at a lower mean effective stress but in the range of lightly over consolidated samples. Having two points on TY, (T_1, p'_1) and (T_2, p'_2) , the reference temperature T_c has been calculated from the following expression:

$$T_c = \exp\left(\frac{p'_1 \ln(T_2 - T_0) - p'_2 \ln(T_1 - T_0)}{p'_1 - p'_2}\right) + T_0 \quad (5.24)$$

Cui et al's model came to the author's attention after finishing the experiments on M44 clay, and therefore the parameters have had to be determined according to the existing data. C_1 and C_2 are estimated from equation (5.25) performing two heating tests on two highly over consolidated samples in which the expansion-contraction behaviour is observed.

$$T_{HC} = \frac{1}{C_2} \ln \frac{1}{C_1} \frac{p'}{p'_{c0}} + T_0 \quad (5.25)$$

α_2 is the elastic coefficient of thermal expansion used for determination of thermal elastic strain and it can be obtained from a cooling test at slow rate. It is considered that during the cooling period the thermal strain is reversible. The parameter "a" governs the thermal plastic strain and can be determined from (5.6) and the substitute parameter α_p . The plastic volumetric strain when reaching the TY yield curve is defined by α_1 . It can be determined by heating an OC sample and loading it at constant temperature. α_1 has been considered to be equal to λ for M44 clay.

5.5 Validity of formulations

In order to check the validity of the formulations, the predictions of Cui's model for tests on Boom clay (Figure 5.2) are reproduced here. The parameters used are: $\kappa = 0.046$, $\lambda = 0.178$, $M = 0.87$, $G = 94.61$ MPa, $\alpha_0 = 3.93 \times 10^{-3}$ per°C, $T_c = 2000^\circ\text{C}$, $C_1 = 0.5833$, $C_2 = -1.908 \times 10^{-2}$ per°C, $\alpha_2 = -5 \times 10^{-5}$ per°C and $a = 0.982$. The sample in this test (Baldi et al 1991) was mechanically consolidated to 6 MPa, mean effective stress then unloaded to 1 MPa (OCR = 6) and subjected to a cycle of heating cooling between 20°C and 95°C . Then the sample was reloaded in two steps to 3 MPa (OCR = 2) and to 6 MPa (OCR = 1) mean effective stress and at each step was subjected to a similar thermal cycle. Figure 5.6 demonstrates the thermo-mechanical path in the above experiment during reloading and thermal cycles. As it can be seen in the graph heating the sample to 95°C at $p' = 1$ MPa (1-2) activates the initial thermal yield locus (TY₀) soon after heating starts and expands it to TY₁. Therefore both thermal elastic and plastic strains are occurring right from the beginning. The resultant thermal volumetric strain will be expansive before the thermo-mechanical path reaches the HC₀ curve at 85.6°C after which thermal contraction occurs up to 95°C . The subsequent cooling just causes thermal elastic strain (2-1). In the second step when the sample is loaded from 1 MPa to 3 MPa mean effective stress, the consolidation path crosses neither TY₁ nor LY₀ yield curves, so only mechanical elastic volumetric strain occurs. The subsequent thermo-mechanical path (3-4) intersects TY₁ but not LY₀ when the heating starts and similar to the first stage of heating only thermal elastic and plastic strains are generated.

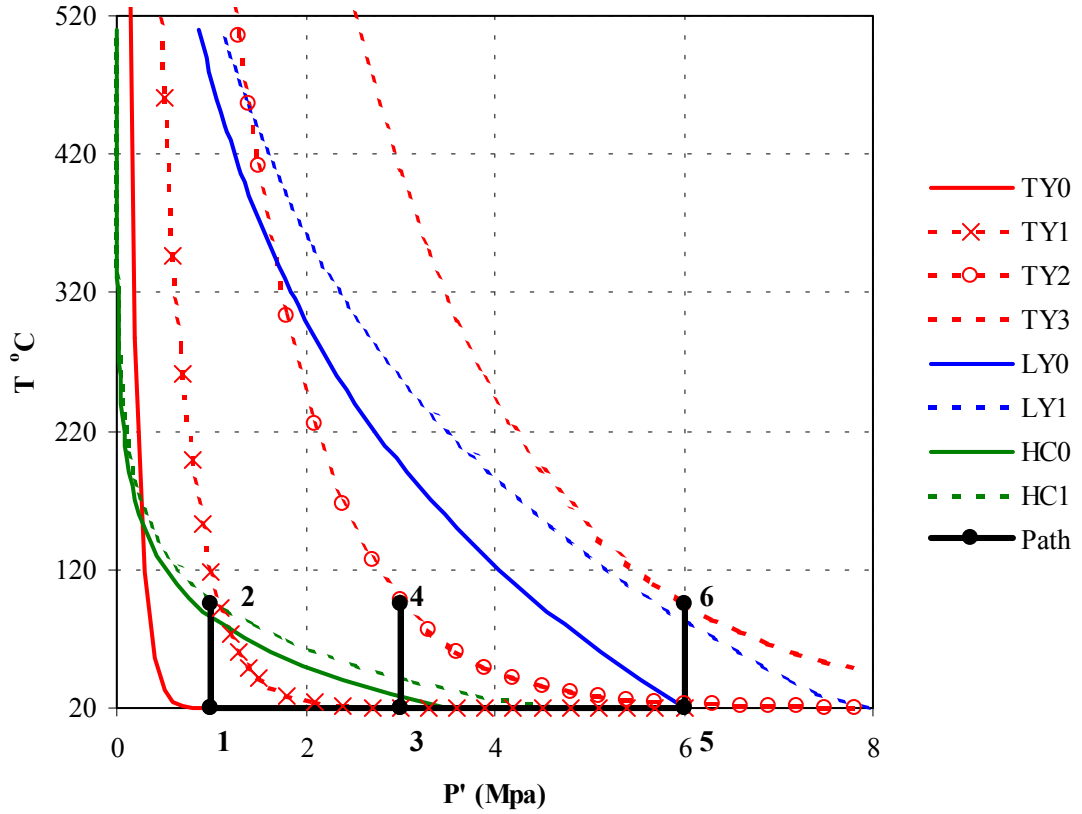


Figure 5.6 Thermo-mechanical path for sample of Boom clay

The thermal hardening expands TY_1 to TY_2 but the LY_0 and HC_0 curves remain the same. The cooling path (4-3) again only causes elastic strain. In the last step, analogous to the second step, the mechanical reloading path (3-5) does not cross either yield loci and only mechanical elastic strain is generated. In the subsequent heating to 95°C (5-6) the thermal consolidation path intersects both TY_2 and LY_0 and produces both thermal and mechanical elastic-plastic strains leading to more thermal hardening, and this in turn shifts HC_0 , LY_0 and TY_2 to HC_1 , LY_1 and TY_3 respectively. Like the other two cooling periods the following cooling period to 20°C (6-5) generates only thermal elastic strain. Figure 5.7 shows the experimental observation by Baldi et al (1991) together with predicted results by Cui et al (2000). Figure 5.8 presents the reproduced data from the implementation of Cui et al's model in the current study. In order to keep the compatibility with Figure 5.7, contractions have been considered positive and expansion negative.

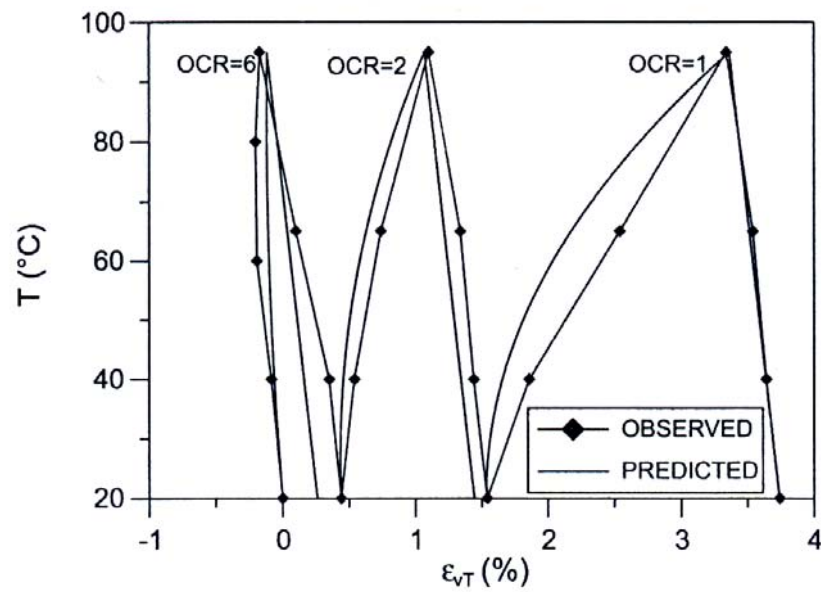


Figure 5.7 Predicted values by Cui et al (2000)

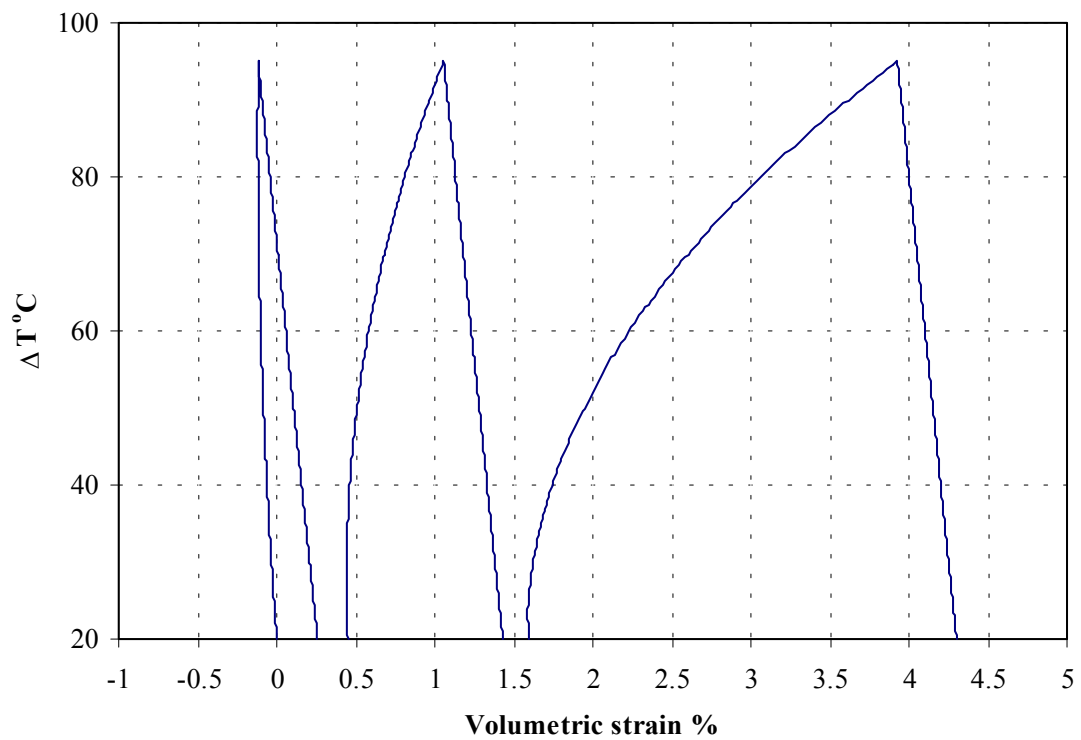


Figure 5.8 Reproduced Boom clay results from Cui's model

According to Figure 5.7 the model predictions are satisfactory and the expansion-contraction response has been well established. By comparing Figures 5.7 and 5.8 it can be clearly noticed that during the first two thermal cycles (OCR = 6, OCR = 2) the

reproduced graph coincides with the Cui et al's results but at the third thermal cycle ($OCR = 1$) the calculated plastic volumetric strain is about 0.5% higher than the reported value by Cui et al (2000). The formulations and all calculations were checked several times and all led to the same results presented in Figure 5.8. The thermal plastic strain has been found to be very dependent on α_p and the value of α_p is constant for normally consolidated and lightly over consolidated samples and was given by equation (5.10). As it was mentioned earlier, the value of α_p is very sensitive to changes in parameter "a" and the reported value for "a" in Cui et al's paper is 0.982 for Boom clay. One possible reason for the observed inconsistency in Cui et al's result could come from using a different value for "a" to match the results. Careful examination of parameters has shown that the small variation of "a" from 0.982 to 0.980 solves the problem and creates similar results as shown in the Figure 5.7. The high sensitivity to parameter "a" could be one of the major disadvantages of this model because as it was shown before very small changes in "a" could lead to a significant error in predictions of thermal plastic volumetric strain. The term "a" is a shape parameter close to unity (Cui et al 2000) and it can be easily ill estimated.

5.6 Predictions and comparison with experimental data

In addition to parameters reported in table 5.2 the following parameters are also needed to model the thermo-mechanical behaviour of M44 clay according to Cui et al's approach. These parameters are extracted from experimental results reported in chapter 4.

- $\alpha_s = 0.35 \times 10^{-4}$, $1/^\circ\text{C}$
- $\alpha_0 = 3.99 \times 10^{-3}$, $1/^\circ\text{C}$
- $T_C = 522^\circ\text{C} \text{ \& } 142^\circ\text{C}$
- $C_1 = 0.4 \text{ \& } C_2 = -1.47 \times 10^{-2}$, $1/^\circ\text{C}$
- $\alpha_2 = -1.82 \times 10^{-5}$, $1/^\circ\text{C}$
- $a = 1.00578$

It should be noted that the above parameters were calculated and in some cases estimated from the strains measured by the GDS and factored internal LVDT

measurements during heating and cooling. It was shown in chapter 4 that the volumetric strains determined from the LVDTs (using the conversion factors from Table 4.1 to allow for the non-isotropic deformations) were more reasonable during cooling-reheating of sample HTUO17, showing contraction during cooling and expansion upon reheating, so they were used for determination of parameters α_2 and "a" which are related to thermal volumetric strains.

5.6.1 Isotropic thermo-mechanical Consolidation

In order to further investigate the validity of Cui et al's model regarding the thermo-mechanical volumetric strains of M44 clay, experimental results from samples HTUO14 and HTUO17 are considered here. Figure 5.9 shows the thermo-mechanical path and variations of yield loci with thermo-mechanical loading for HTUO14. For the purpose of simplicity just stages with thermal loading are considered. As mentioned in the previous chapter, the sample was initially consolidated (mechanically) to $p' = 700$ kPa and unloaded to $p' = 100$ kPa ($OCR = 7$) then it was heated to 100°C under constant mean effective stress (1-2). The LY_0 locus crosses the p' axis at 0.7 MPa and unloading to 0.1 MPa just creates elastic mechanical strain. At point 1, the sample has not experienced any temperature elevations so the TY_0 curve is very close to $T = 22^\circ\text{C}$ and HC_0 is defined by C_1 and C_2 parameters. From point 1 to 2 (heating from 22°C to 100°C , the consolidation path crosses the TY_0 locus giving rise to plastic thermal strain but the resultant thermal strain (elastic and plastic) is expected to be expansive until the path crosses the HC_0 curve (transition) at 78°C after which contraction is observed. In consequence the TY_0 curve moves to TY_1 . The changes in specific volume and volumetric strain with temperature are demonstrated in Figures 5.10 and 5.11 respectively. The observed contraction-expansion behaviour has been identified by this model. The reduction in specific volume in Figure 5.10 should not be interpreted as contraction (see earlier discussion in chapter 4). It can be seen in both graphs that the predicted values are much less than the observed values for both specific volume and volumetric strain. The model shows a maximum of about 0.1% volumetric strain while the observed values calculated from GDS and internal LVDTs (factored) indicate about 0.9% and 1.3% volumetric strain respectively. The discrepancy between observed and predicted volumetric strain in this case could have two possible reasons:

1- the model assumes that under HC_0 the volumetric strains are mainly elastic and arising from expansion of solid particles, whereas there could be some additional expansion due either to water absorption at high OCR or to creep.

2- the value of α_2 , the drained coefficient of thermal expansion, was estimated from the thermal cycle of a normally consolidated sample, and this could differ from α_2 at high OCRs.

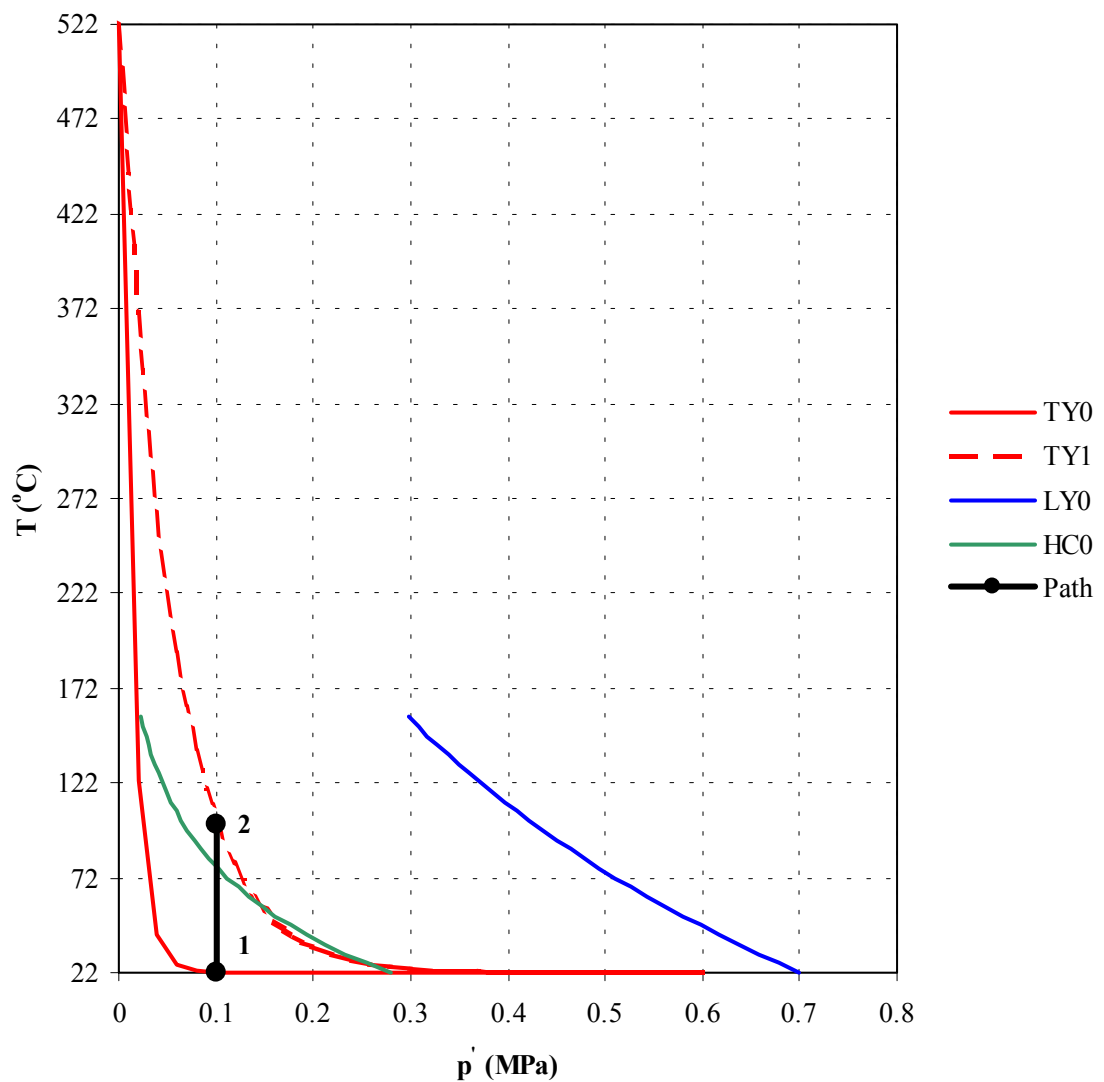


Figure 5.9 Thermo-mechanical path for sample HTUO14 (OCR = 7)

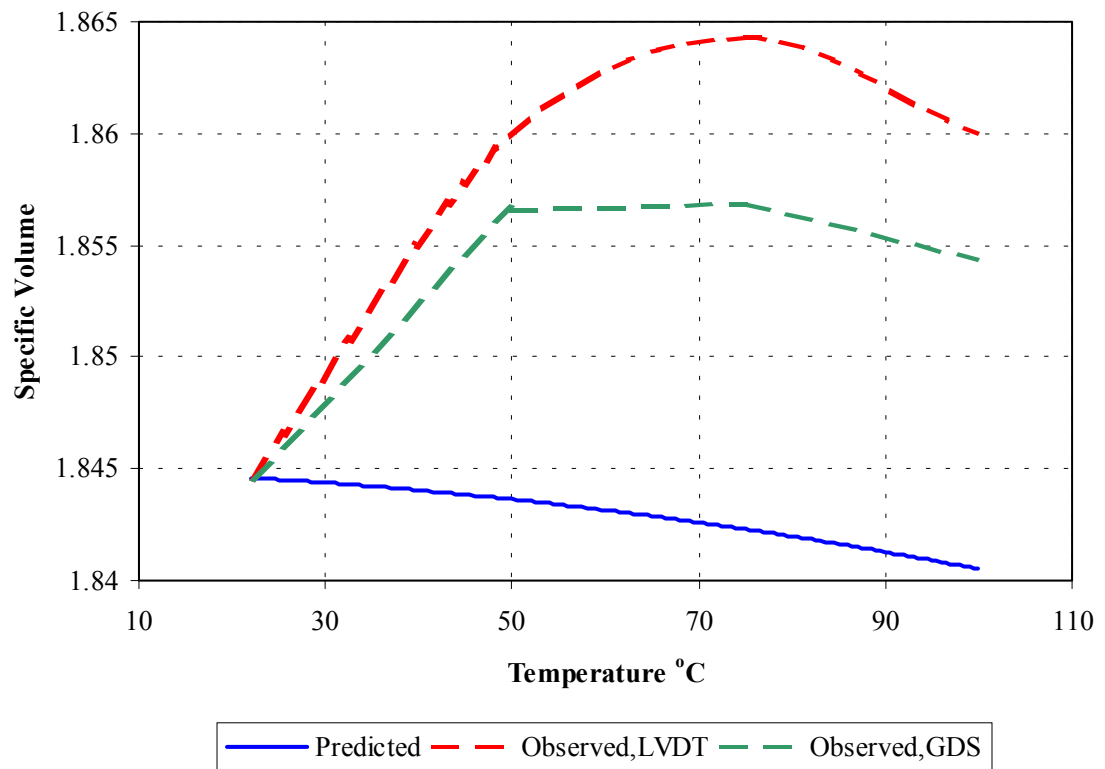


Figure 5.10 Variations of specific volume with temperature for M44 Clay (HTUO14)

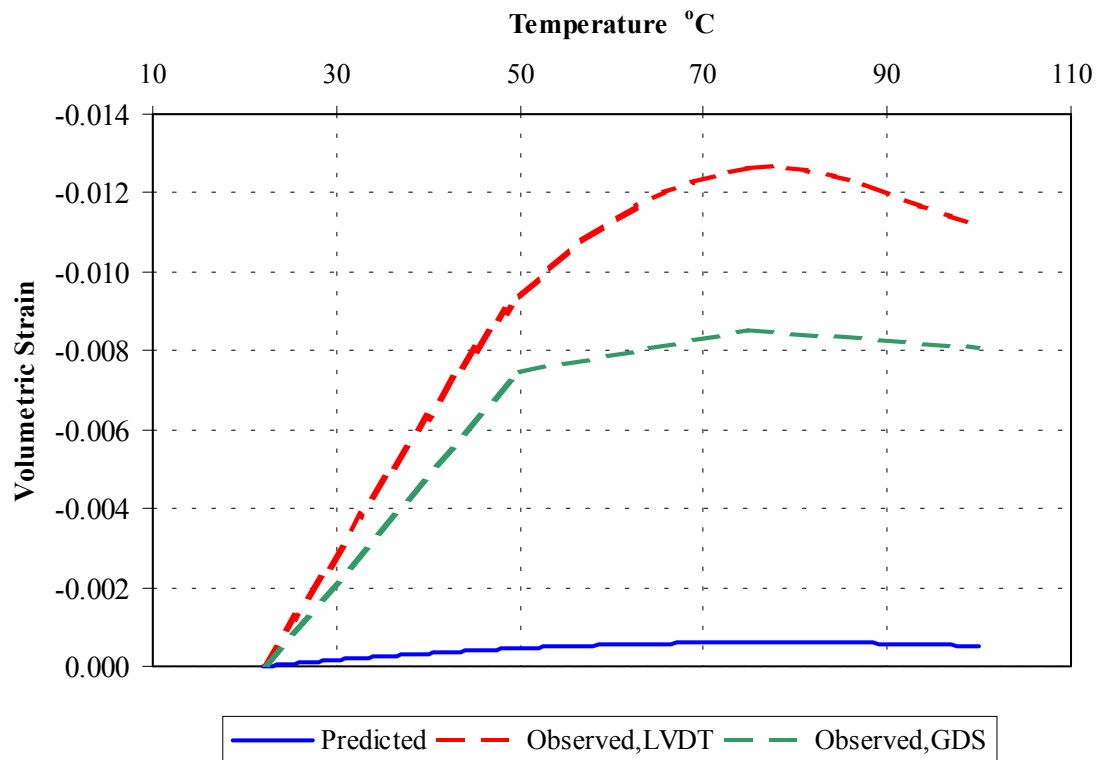
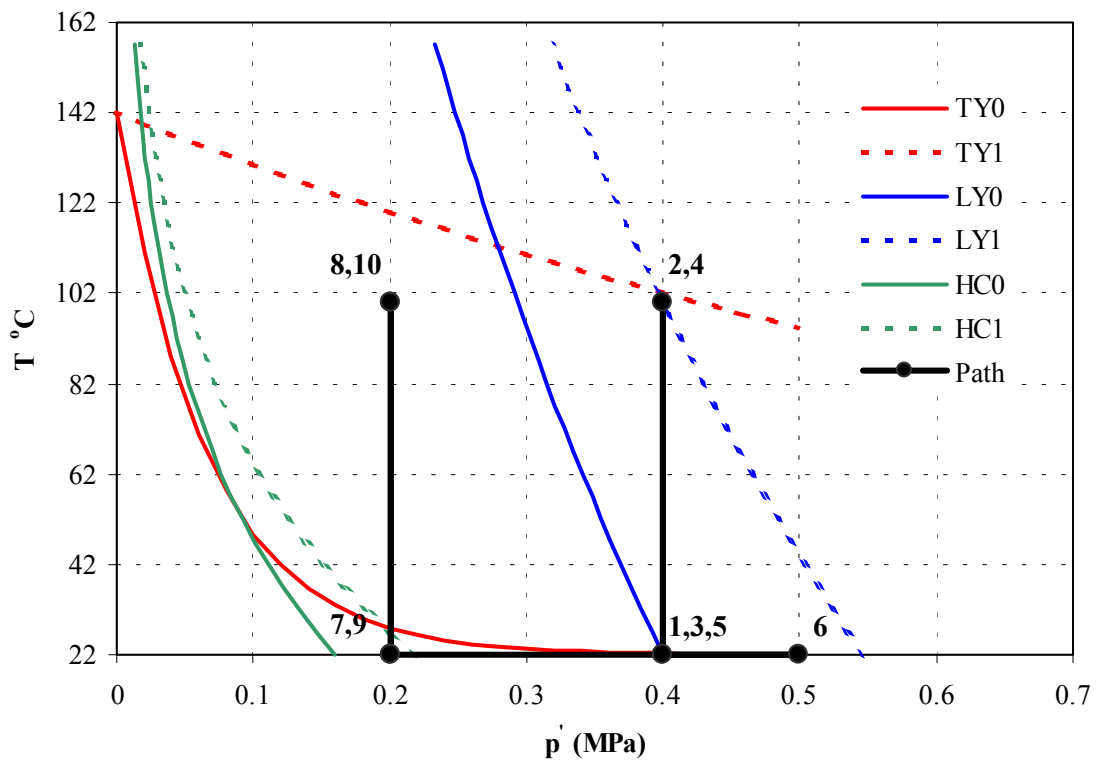


Figure 5.11 Comparison between predicted and observed volumetric strain for M44 clay (HTUO14)

Careful examination of the results also shows that the strain estimated from the LVDTs is slightly higher than the observed strain obtained from the GDS. As mentioned in the previous chapter this is a consequence of non-uniform sample deformation during thermal consolidation, and the need to scale the LVDTs to estimate the volumetric strain because the PG measuring radial displacement was out of range.

Figure 5.12 demonstrates the thermo-mechanical path followed during consolidation of sample HTUO17 in the T - p' plane. The initial normal mechanical consolidation part to $p' = 400$ kPa has been omitted for simplicity.



5.12 Thermo-mechanical path for sample HTUO17 (OCR = 2.5)

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 mechanical 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 just thermal elastic strain during 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 5.12).

The predicted variations of specific volume and volumetric strain with temperature are compared with the values estimated from the internal LVDTs in Figure 5.13 and 5.14.

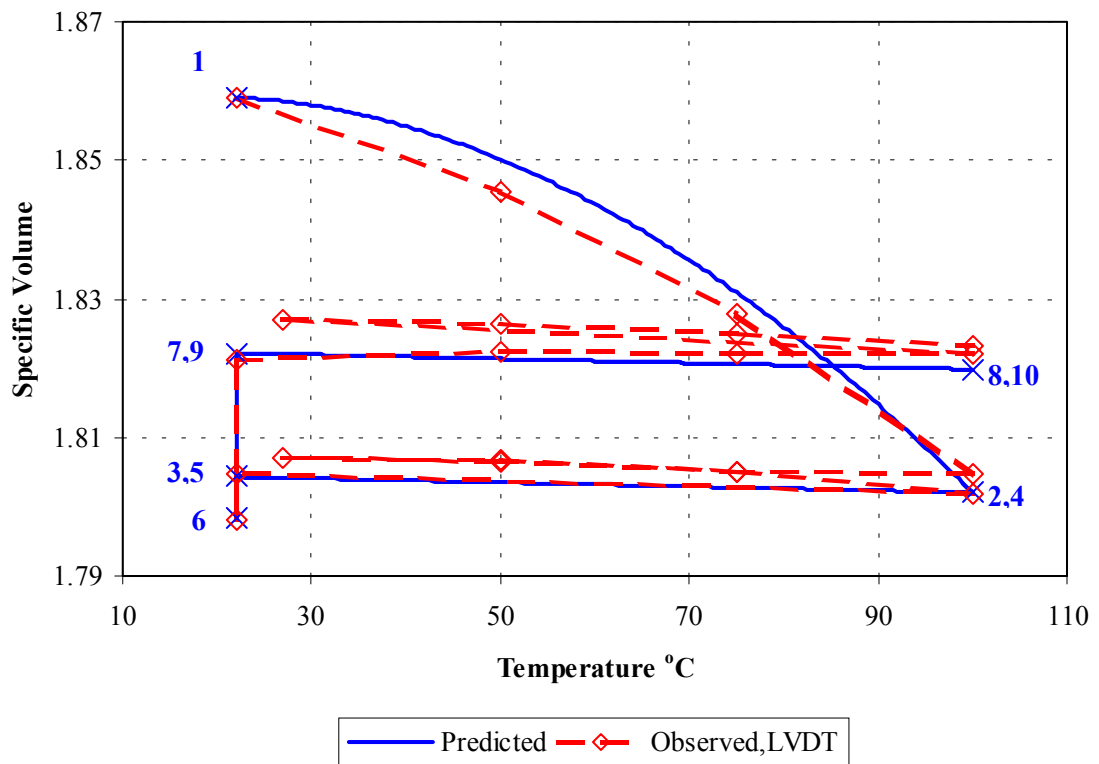


Figure 5.13 Observed and predicted variations of specific volume with temperature (HTUO17)

It can be seen from both graphs that the predicted volumetric strains during thermal cycles are in good agreement with the experimental results estimated from the LVDTs. The good correlation between LVDTs and predictions is partly related to the determination of the modelling parameters from measurements made by the LVDTs.

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 of the LVDTs.

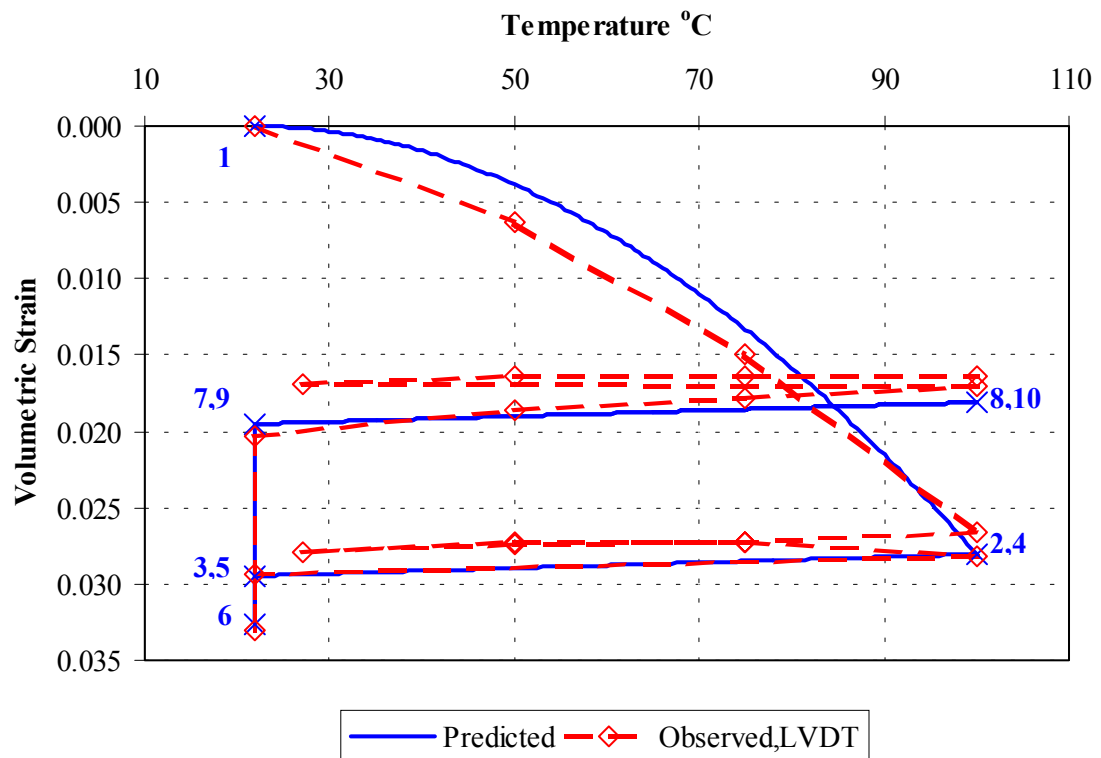


Figure 5.14 Observed and predicted variations of volumetric strain with temperature (HTUO17)

From the two experiments discussed here it might be concluded that the Cui et al's model can correctly reproduce the expansion-contraction behaviour reported in sample HTUO14 and many other studies (such as Baldi et al 1991). However, it significantly underestimates the thermal volumetric strains of the highly overconsolidated sample HTUO14 ($OCR = 7$), because the model assumes that at high OCRs the thermal volumetric strains are mainly elastic and direct results of thermal expansion of soil particles even when the sample is heated for the first time. Similarly, it slightly underestimated the thermal expansion of the lightly OC sample, HTUO17 ($OCR = 2.5$), when it was heated for the first time (Figure 5.14, 7-8). 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 5.14) because the exponential curve (equation 5.6) used for thermal plastic volumetric strain of NC

samples appears to be slightly different from the observed thermal consolidation curve (TCC). It should be noted that expansion-contraction behaviour may not be seen in highly over consolidated samples with a recent stress history of reloading (Burghignoli et al, 2000). More experimental data are required to confirm Burghignoli et al's results and to improve Cui et al's model. A more accurate model would require a non-linear mechanism within the yield locus.

5.6.2 Undrained thermal volumetric and pore pressure changes

There was not enough information provided in Cui et al's model to allow predictions of thermally induced pore pressure, but attempts were made to use this model to predict the volumetric strains during undrained heating. Sample HTUO16 has a similar mechanical consolidation history to sample HTUO17 before the beginning of heating so the initial TY, LY and HC should be the same as shown in Figure 5.12 (TY₀, LY₀ and HC₀). Undrained heating from 22°C to 100°C will create an inclined path in T-p' plane because heating increases the pore pressure and therefore reduces the mean effective stress, p', and increases the OCR. This path is under LY₀ but crosses the TY₀ locus right from the start of heating. Thus there should be elastic thermal and mechanical volumetric strains and thermal plastic strains in the sample. The equation for incremental changes in undrained volumetric strain can be written as follows:

$$d\varepsilon_v = d\varepsilon_{vT}^e + d\varepsilon_{vm}^e + d\varepsilon_{vT}^p \quad (5.26)$$

Substituting 5.1 and 5.7 into 5.26 and considering $d\varepsilon_v = (\alpha_s + \alpha_w)dT$ leads to:

$$(\alpha_s + \alpha_w)dT = \alpha_2 dT + \frac{\kappa dp'}{vp'} + \alpha_p [\exp(\alpha_p \Delta T) - a]dT \quad (5.27)$$

If α_p is known dp' would represent the change in pore pressure for a temperature increment of dT . It should be noted that α_p is constant (see equation 5.10) only when the sample is normally consolidated or lightly over consolidated otherwise it has to be determined by solving equation 5.9 using T_{HC} which is a function of p' itself (see equation 5.25). Initial calculations of pore pressure are relatively simple when the sample is in the lightly over consolidated region, but as the degree of over consolidation increases due to undrained heating the calculations become very complicated and time consuming because of the interdependency of α_p , p' and T_{HC} . In consequence

simulation of pore pressure development during undrained heating using Cui et al's model was not considered to be viable.

5.6.3 Deviatoric stress-strain response

As it was mentioned earlier the modified Cam clay model (Roscoe and Burland 1968) has been employed here for predictions of triaxial stress-strain response of M44 clay at different temperatures. It has been assumed that the associated flow rule is applicable here and both INCLs and CSLs shift equally to a lower location in v - p' plane due to any increase in temperature. The predictions of the model are compared with the experimental results from undrained and drained isotropic triaxial shear tests of normally (NC) and over consolidated (OC) samples. The parameters in Table 5.2 have been used for modelling.

5.6.3.1 Undrained triaxial compression

Typical experimental results from NC samples of M44 clay are compared with the corresponding output of the Cam clay model in Figures 5.15, 5.16 and 5.17. In the legend OB, CC and the number indicate observation, Cam clay and temperature respectively. The plotted values are deviator stress, q , and mean effective stress, p' , and pore pressure changes, Δu , which have been normalized by p'_c , the mean effective stress at the end of thermo-mechanical consolidation. As can be seen in Figure 5.15 the predictions show a reduction in shear strength with increase in temperature, but this is less than observed. The initial slopes of the predicted curves are all the same because Poisson's ratio has been considered to be constant at all temperatures. The observed slopes of the curves between 0.3 and 0.5 (normalized deviatoric stresses) diverge significantly from the predictions. This suggests that the elliptical shape of the yield locus is not correct for this clay. It was shown in chapter 4 that the development of pore pressure during undrained shear tests is only slightly affected by temperature, and only a single curve representing the observed behaviour at all temperatures is shown on Figure 5.16. This is also predicted by the model, which as shown in Figure 5.16 indicates only a minor reduction in the maximum pore pressure. 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.

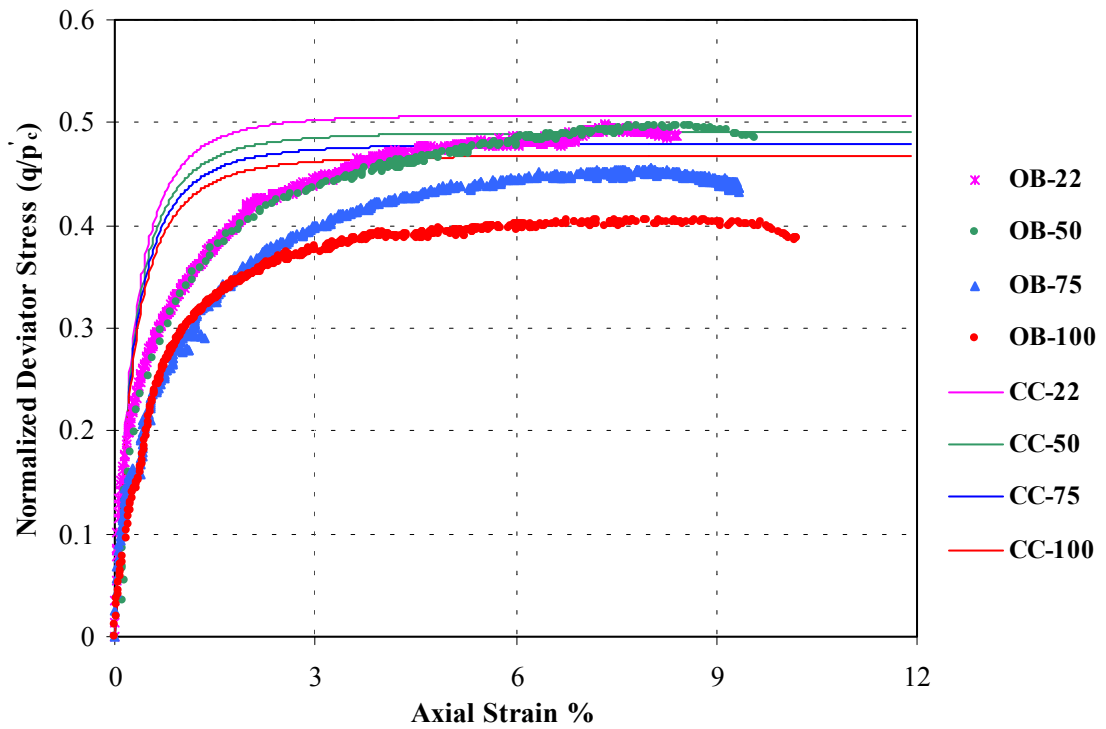


Figure 5.15 Observed and predicted undrained stress-strain response of NC samples of M44 clay

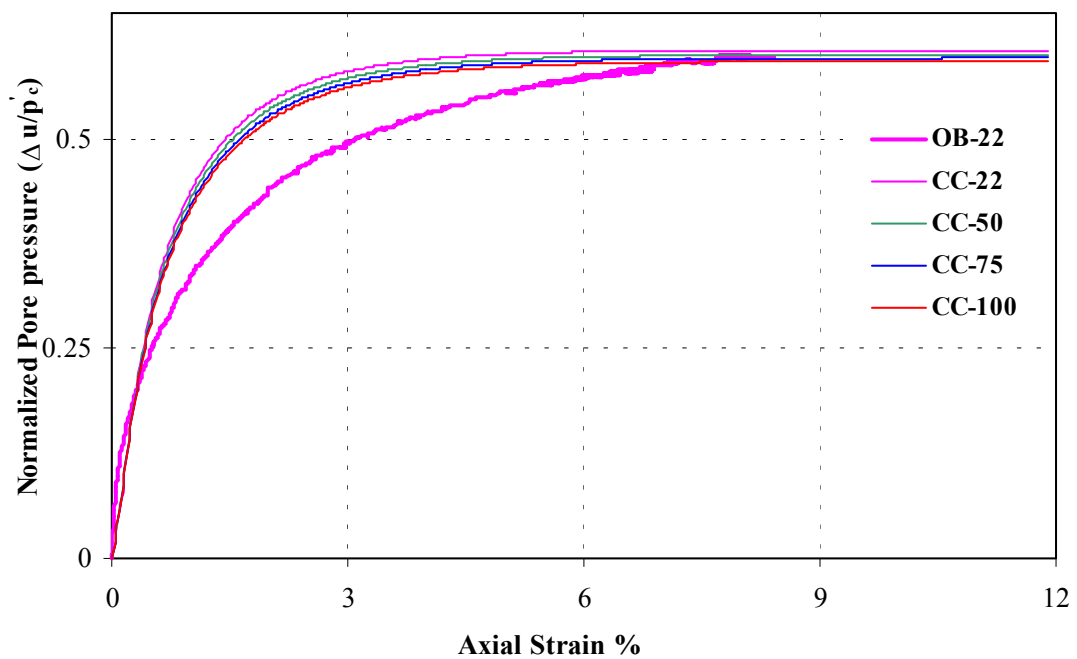


Figure 5.16 Observed and predicted pore pressure variations of NC samples at different temperatures

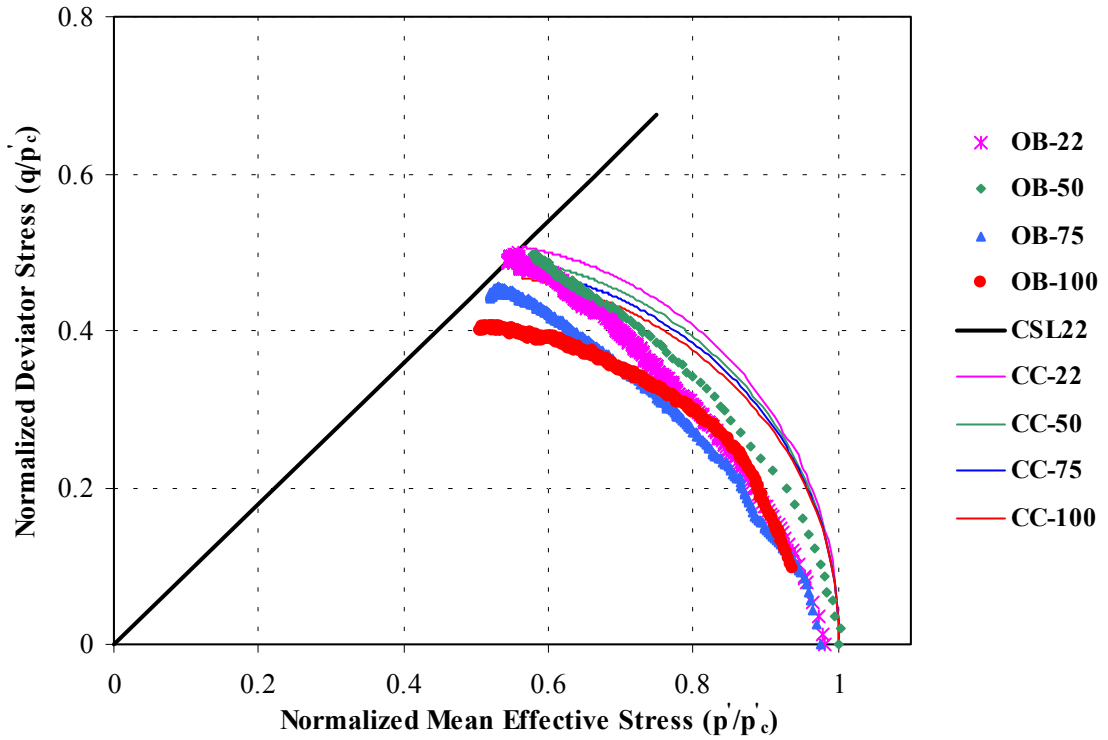
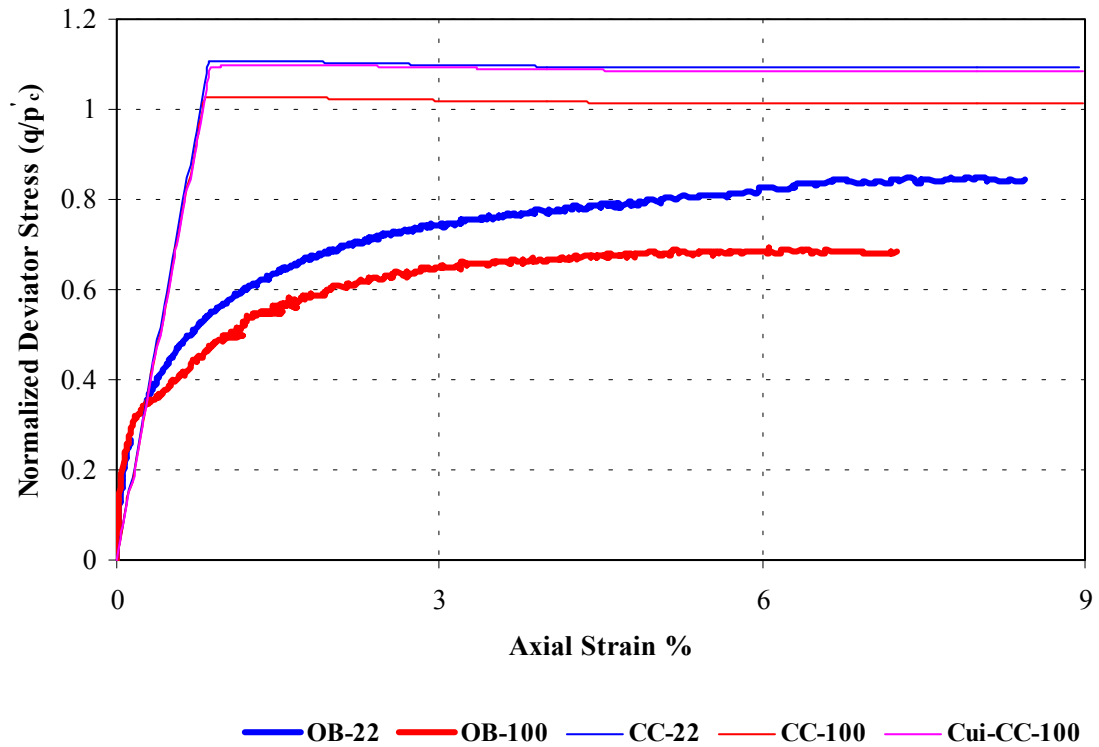


Figure 5.17 Observed and predicted undrained stress paths of NC samples at different temperatures

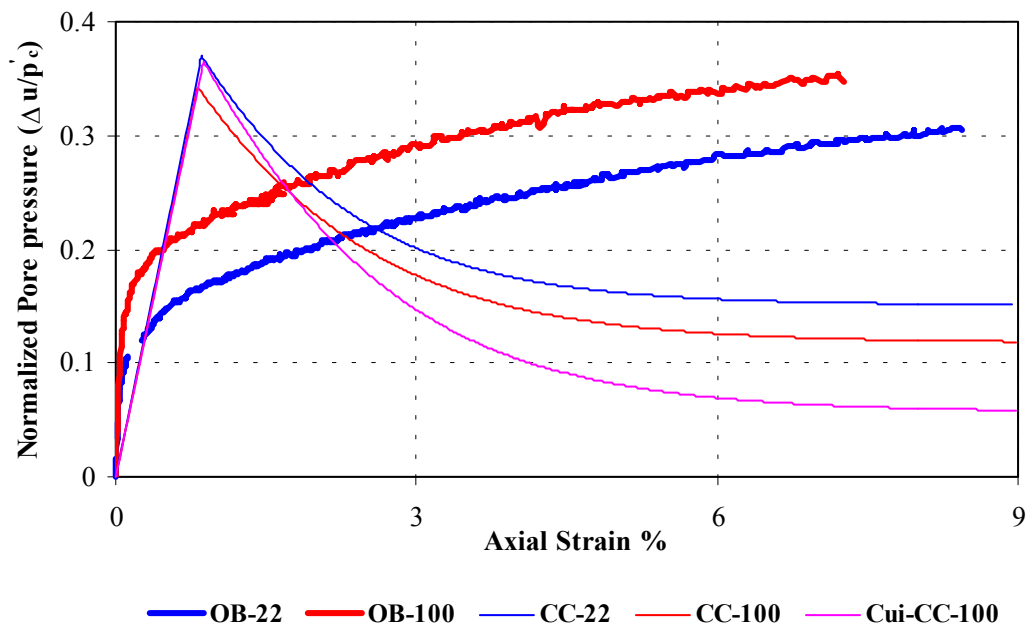
The effective stress paths in Figure 5.17 also demonstrate the reduction in the normalized effective stresses with temperature. The predicted responses approach the critical state line. In the model the slope of the CSL reduces with temperature, but only the CSL22 is shown for clarity of the graph.

Lightly over consolidated samples have shown reductions in the shear strength with increase in temperature in undrained triaxial compression at elevated temperature, similar to the NC samples. Figures 5.18, 5.19 and 5.20 present the observed and predicted values of q/p'_c versus ϵ_a , $\Delta u/p'_c$ versus ϵ_a , q/p'_c versus p'/p'_c for some lightly over consolidated samples ($OCR = 2.5$) during undrained shearing. The curve marked Cui-CC is for the Cam clay model using a bigger initial LY locus (higher $p'_0 = 545$ kPa) due to thermal hardening (Cui et al, 2000) that implies an apparent $OCR = 2.7$. It can be seen in Figure 5.18 that both the CC and Cui-CC responses significantly overestimate the maximum deviatoric stress reached, but unlike CC, Cui-CC does not reproduce the reduction in deviatoric stress with temperature. This could be a consequence of the

increase in the size of the LY yield locus during thermal consolidation. The modified Cam clay is known not to give good predictions for deviatoric loading of OC samples.



5.18 Observed and predicted undrained stress-strain behaviour of lightly OC samples (OCR = 2.5)



5.19 Observed and predicted pore pressure developments of lightly OC samples (OCR = 2.5)

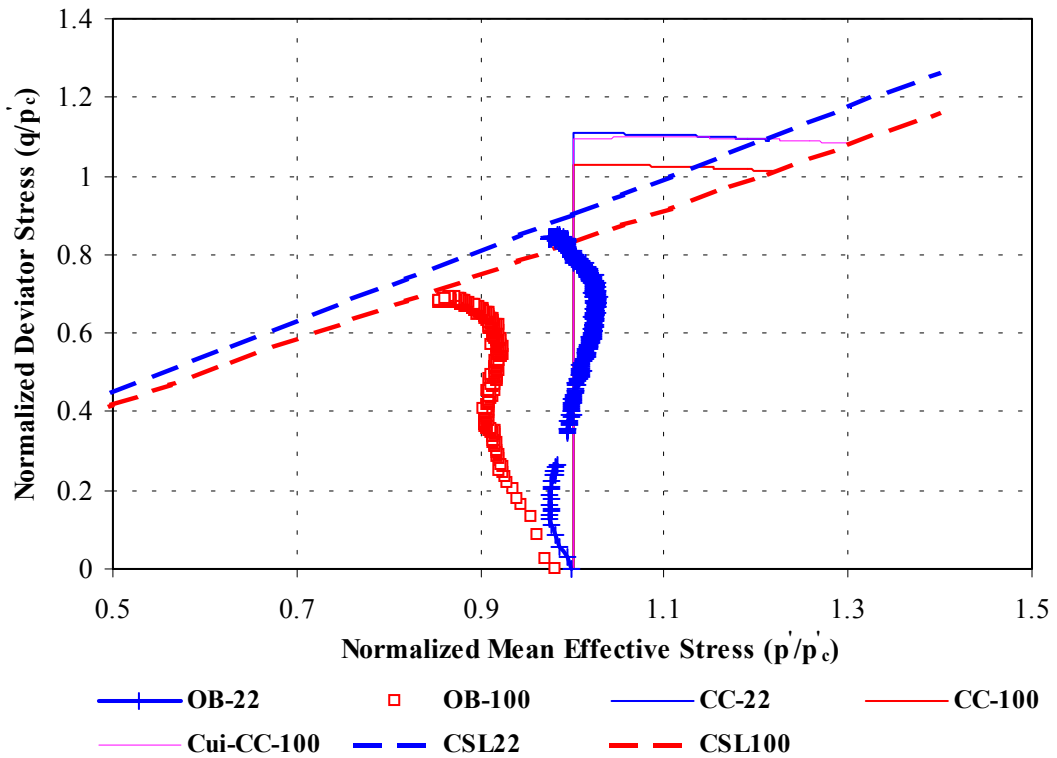


Figure 5.20 Observed and predicted undrained stress paths of lightly OC samples ($OCR = 2.5$)

By careful examination of Figure 5.19 it can be noticed that while the predicted pore pressure development is typical for overconsolidated samples this type of behaviour has not been observed in the experiment. Unlike the experiment both CC and Cui-CC provided lower pore pressure development at elevated temperature. The stress paths in Figure 5.20 confirm the above observations. As can be seen in the graph the predicted stress path initially travels vertically until it crosses the CSL reaches yield and then moves to the right to reach the CSL. It is clear that the experiments and the model's predictions travel in opposite ways to reach the CSL. This could be related to the assumed separation between the INCL and CSL being incorrect.

The results of undrained shear tests on two highly overconsolidated samples ($OCR = 7$) at 100°C are compared with the output data of the CC and Cui-CC models in Figures 5.21, 5.22 and 5.23. It was mentioned in chapter 4 that sample HTUO14 has been mechanically loaded to $p'_c = 700 \text{ kPa}$ and unloaded to $p'_c = 100 \text{ kPa}$ first and then thermally consolidated to 100°C while sample HTUO15 was first consolidated to 100°C before mechanical consolidation and over consolidation.

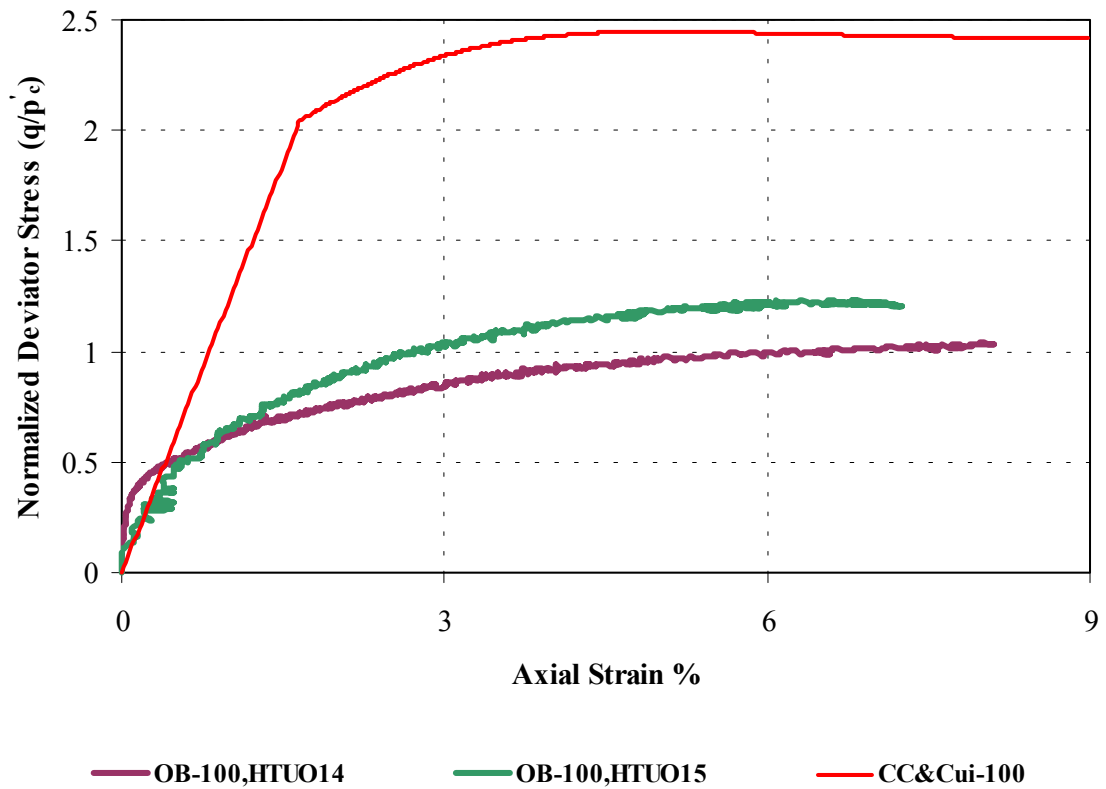


Figure 5.21 Observed and predicted undrained stress-strain response of highly OC samples (OCR = 7)

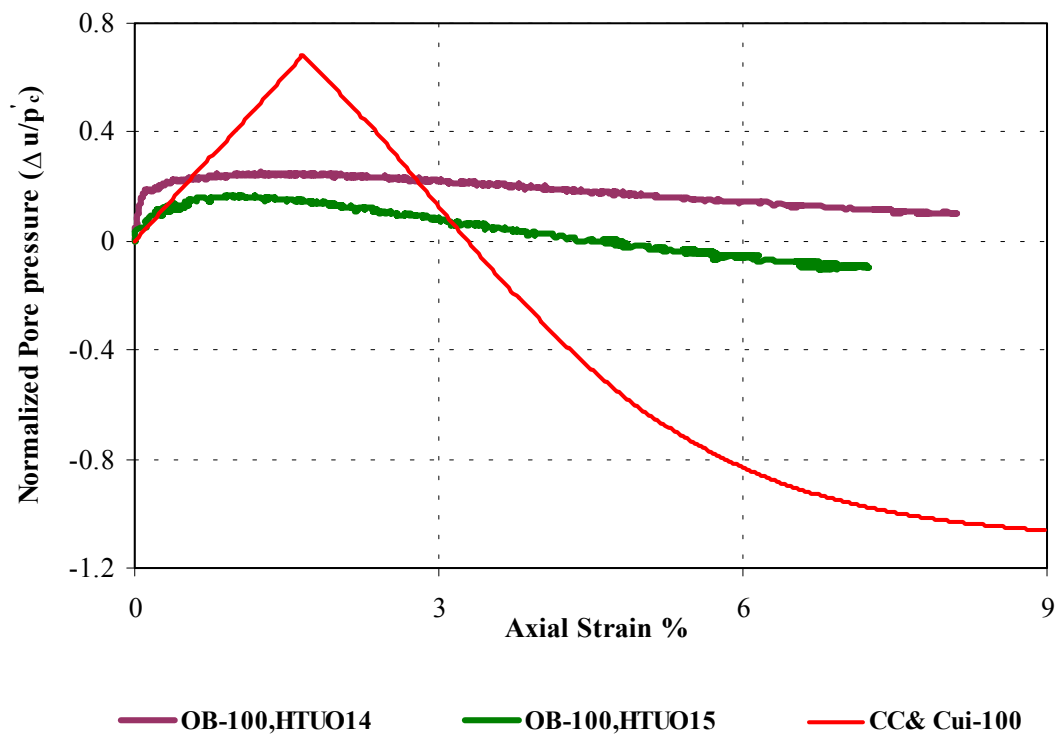


Figure 5.22 Observed and predicted pore pressure development of highly OC samples (OCR = 7)

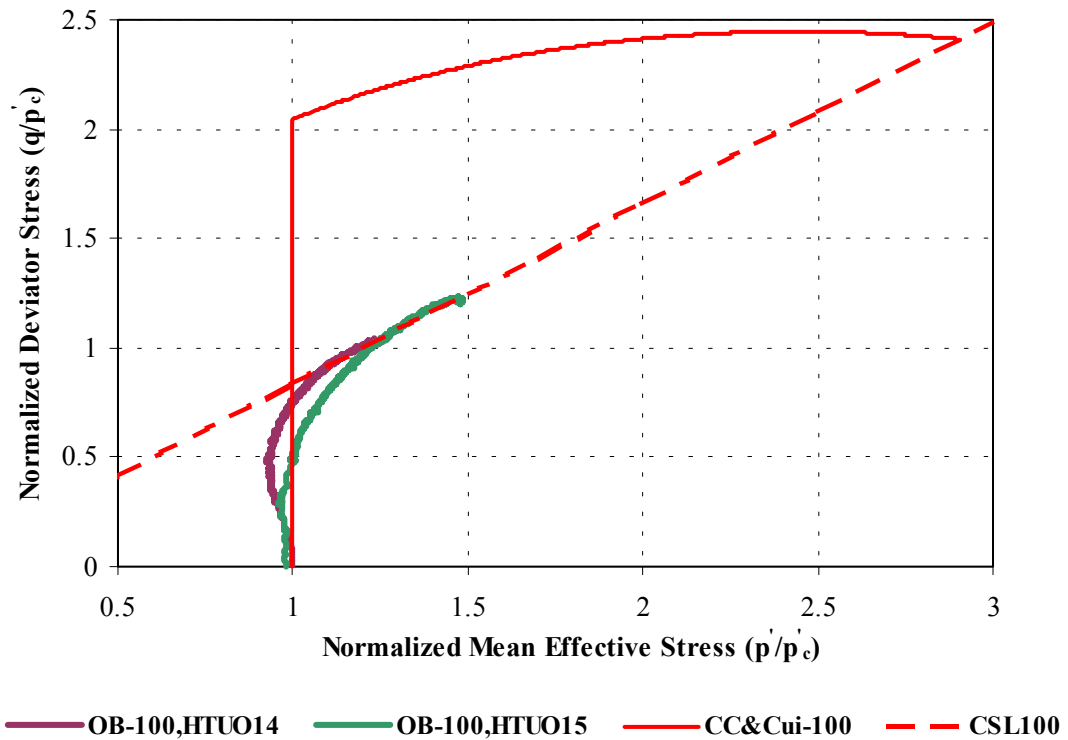


Figure 5.23 Observed and predicted undrained stress paths of highly OC samples (OCR = 7)

Figures 5.21 and 5.22 show the observed and predicted variations of normalized effective stress and normalized pore pressure with axial strain. The CC and Cui-CC models have one prediction for both samples and are not capable of predicting this type of behaviour. Like the lightly OC samples the peak deviator stresses and the maximum pore pressures have been greatly overestimated for the highly OC samples. As mentioned earlier the modified Cam clay is known to produce such behaviour for OC samples. This is related to the assumption of an elliptical yield locus and the constant spacing ratio (vertical separation between INCL and CSL in v - p' plane) at different temperatures. Tests with OCR = 7 at room temperature are required for further discussion and comparison. It is clear from Figure 5.23 that despite the overestimations of maximum deviator stress by the models the trend of the predicted stress path is similar to the observations. From Figures 5.21 and 5.22 it can be noticed that the samples present moderately OC behaviour and it seems that the effects of over consolidation have been partly removed by heating to 100°C. To the author's knowledge neither Cam clay nor any other model presented in the literature is able to predict such a phenomenon.

5.6.3.2 Drained triaxial compression

The behaviour of M44 clay during drained shear tests on NC samples has also been simulated using the Modified Cam clay model and the results are demonstrated in Figures 5.24 and 5.25. 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 number of experimental stress-strain curves (Figure 5.24), it is not clear whether the strength increases or decreases with increase in temperature. Considering also the results of Kaolin C1C the observed drained shear strength appears to increase at high temperature with less development of both axial and volumetric strains indicating a more brittle response.

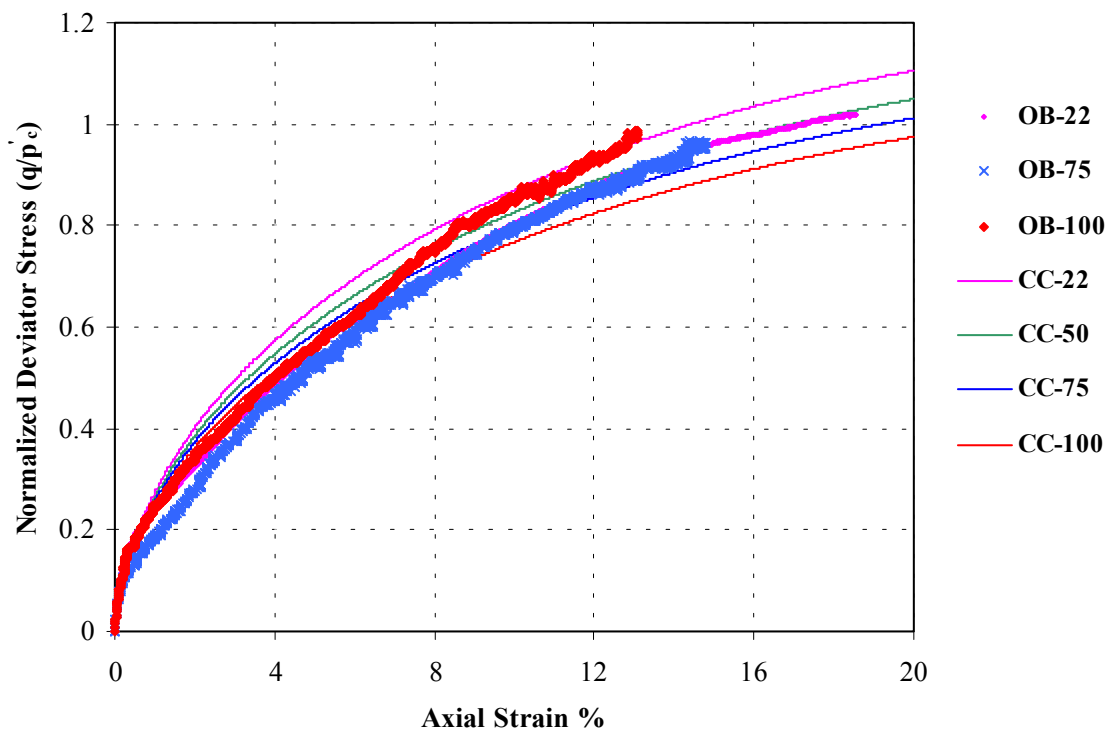


Figure 5.24 Observed and predicted drained stress-strain behaviour of NC samples at different temperatures

The reduction in ductility with temperature shown in Figure 5.25 has been also observed in the current and previous study (Chiu, 1996) for Kaolin C1C. This type of behaviour cannot be predicted by simple soil models and could be related to introduction of some structure into the soil behaviour during drained tests by heating. To produce the observed behaviour the shape of the yield locus needs to change slightly

with increasing temperature. The reduction in the observed volumetric strain at elevated temperature must be considered for future developments of new models.

As expected the predictions of the Cam clay model appear to be more reasonable for NC soils compared to OC soils.

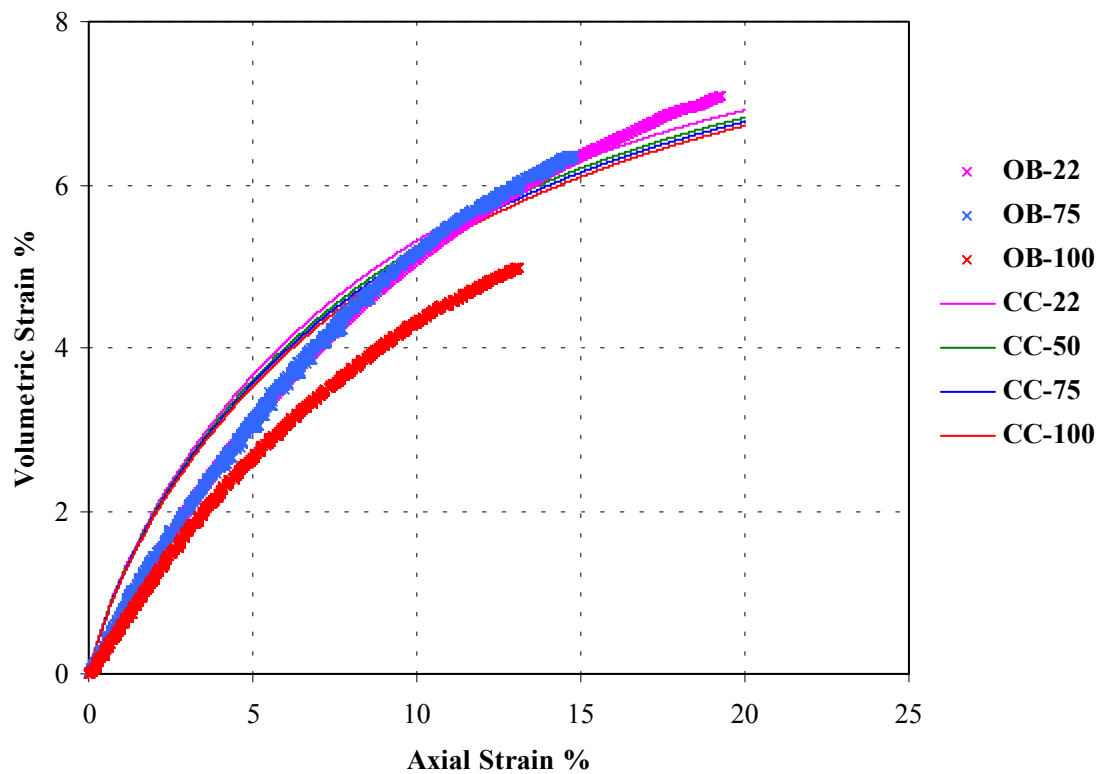


Figure 5.25 Observed and predicted volumetric strain during drained shear test on NC samples

5.7 Summary and conclusion

The background to the thermo-mechanical models proposed for soil has been discussed in this chapter. The models are mainly versions of the Cam clay model with some modifications to include the soil response to temperature variation. Despite a great number of investigations in this area, the complex thermo-mechanical behaviour of soil is not completely understood and consequently the models developed have sometimes been associated with errors which have been discovered with progress in experimental techniques. The predictions of Cui et al's model for thermally induced drained volumetric changes have been critically examined using the experimental data from tests on Boom clay and M44 clay. Reproduction of test result on Boom clay reported by

Cui et al's model was not possible using the same parameters reported in Cui et al (2000). A sensitivity analysis of parameters revealed that the predicted volumetric strains are very sensitive to changes in parameter "a" but are less affected by changes in other parameters. This might be counted as one of the model's disadvantages because "a" is a shape parameter and could be easily ill estimated. Adjustment of "a" from 0.982 to 0.980 altered the predicted volume strain by 25% and reproduced the reported data by Cui et al for Boom clay. Such an error of 0.002 might be easily made during curve fitting. For M44 clay in the range of NC and lightly OC ($OCR = 2.5$) samples the model predicted contraction upon drained heating and the calculated volumetric strains were in good agreement with the experimental results. Similarly the amount of elastic volumetric strain in the cooling period was reasonably predicted but the amount of thermal expansion during first heating at $OCR = 2.5$ was slightly under estimated. For highly OC ($OCR = 7$) samples, the model correctly established the expansion-contraction behaviour but significantly underestimated the volumetric strain occurring during heating. As was mentioned earlier, Cui et al's model needs more improvements in order to facilitate the prediction of thermally induced pore pressure and volume changes during undrained heating

The observed behaviour of M44 clay during deviatoric loading was compared with the predictions of the Modified Cam clay model (Roscoe and Burland, 1968) using different M values at various temperatures. The predicted drained and undrained shear responses of NC samples were satisfactorily within the findings of this study presenting lower strength at higher temperature although this trend was not clear for drained conditions. It has been observed that the ductility reduced at higher temperatures during drained shear tests, which could not be predicted by Cam clay.

The modified Cam clay model is known to provide poor predictions for over consolidated samples and this was observed at all temperatures. However, the general qualitative trends with OCR and temperature were correctly indicated.

It can be concluded that the Cui et al's (2000) thermo elastic plastic model, despite the complexity in the modelling and large number of parameters, cannot properly simulate the volumetric changes in the soil due to heating. Further developments in understanding are required to provide more physically meaningful parameters for further model development. In particular the shape of TY locus must be redefined based

on further experimental data and it should be described in a way which is not sensitive to the parameters such as “a”. The TY curve does not include the dependency of volumetric strain to the thermo-mechanical consolidation path (such as those observed by Burghignoli et al 2000). A different mechanism is required to move the TY yield locus based on the OCR and the recent stress history.

SUMMARY AND DISCUSSION

6.1 Background

The literature survey in chapter 2 revealed that despite the greater attention to the thermo-mechanical behaviour of soil in recent years, this subject has still not been fully understood. It has been suggested that in the range of temperature from 20°C to 100°C investigated in this study, neither new crystallization nor conversions of hydroxyl ions are expected.

The results of previous studies of permeability have indicated that both permeability and coefficient of consolidation increase due to heating as a result of a reduction in the viscosity of pore water. However, the absolute permeability is only a function of void ratio and plasticity. It should be noted that these studies have been mainly based on the one-dimensional consolidation and consolidation curve, and very few direct measurements have been reported.

Slow heating under constant effective stress causes contraction or expansion known as thermal consolidation while rapid heating or heating under undrained conditions leads to pore pressure generation. Thermally induced volumetric changes during drained and undrained heating in nearly all studies were determined using external measuring devices.

The effects of temperature on shear strength and stiffness were found to be controversial, although some of these controversies could be explained by examination of the testing conditions and the consolidation histories.

The review of thermo-mechanical modelling of soil indicates that the developed models are based on limited experimental data and on assumptions that may not be true. For example the assumption of increasing κ at elevated temperature by Graham et al (2001) was made to fulfil the expansion-contraction behaviour of OC clay samples during drained heating, but the data show κ decreases with increasing temperature.

Consideration of the above facts leads to a clearer understanding of current state of research on the behaviour of soil at elevated temperature and proves that more reliable experimental data are required to address the uncertainties surrounding the behaviour of soil at elevated temperature.

6.2 Apparatus and Instrumentation

The previously designed high temperature triaxial apparatus (Chiu, 1996) was found to need major modifications before triaxial testing at elevated temperature could begin. A fully automated high temperature triaxial apparatus (FHTTA) was developed in order to automatically monitor and control the triaxial testing at elevated temperature. The modifications are summarized as follows:

- 1) The oven was modified to allow automatic control of temperature by the computer.
- 2) The triaxial cell was coated by a special steel powder to minimise corrosion.
- 3) The ceramic stand was modified in order to accommodate proximity gauges and new LVDT's.
- 4) A new top cap was designed from ceramic material.
- 5) The stiff top drainage line used by Chiu (1996) was found to interfere with the consolidation process and to introduce error in the measurements of axial load. It was removed and instead radial filter strips were employed to speed up the process of consolidation.
- 6) A computer program was developed for monitoring and controlling different devices in the system.

Some of the room temperature triaxial tests before completion of the FHTTA were carried out using a conventional triaxial machine. Permeability tests at temperature

from 22°C to 50°C were carried out using a modified conventional triaxial cell, which was placed in the temperature-controlled oven of the FHTTA.

Finally two types of clay, Kaolin C1C and M44 clay, were selected for triaxial tests at different temperature because, their behaviour at room temperature was found to be reasonably predictable by the modified Cam-clay model.

6.3 Thermo-Mechanical Behaviour of Clay

A series of isotropic consolidation, drained and undrained triaxial tests on NC and OC samples of M44 clay and Kaolin C1C at different temperatures were carried out. The results show that deformation of NC samples during drained heating is mainly plastic and not recoverable upon cooling. For NC samples the thermal compression curve is identical at any 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 p' .

A repeatable hysteresis loop and some residual pore pressure build up is observed in the v - p' plane during undrained thermal cycles of NC and OC samples of M44 clay, demonstrating that the variations of v with effective stress are not linear. The relationship between v and T is non-linear but is quite repeatable for both NC and OC samples. This indicates that during undrained heating the thermal volume changes are direct results of the thermal expansion of water and clay particles. The observed hysteresis loop in pore pressure was not evident in the displacements, and consequently volumetric strain changes, during undrained thermal cycles.

There are series of INCLs in the v - p' plane for various temperatures with a unique slope, λ , and different N values. κ has been found to be dependant on both effective stress and temperature. It reduces with increase in temperature and effective stress level (during mechanical unloading).

The coefficients of thermal expansion of the clay particles, α_s , determined during drained and undrained heating are similar to the value reported by Campanella and Mitchell (1968). Larger α_s values were estimated from undrained heating stages. This might be due to lack of a proper radial displacement measuring devices and

non-uniform deformation of sample or alternatively it could indicate error in the correction for expansion of water. For a reasonable determination of α_s an accuracy of $\pm 10 \mu\text{m}$ or better is needed for measurement of radial displacement. This type of accuracy at elevated temperature under water needs improvements in the small displacement measuring device technology.

The undrained shear strength of NC and lightly OC samples of M44 clay slightly decreases at elevated temperature and is independent from the thermo-mechanical consolidation path. However, for highly OC samples the order of thermal and mechanical consolidation seems to affect the undrained shear strength. The drained shear strength of Kaolin C1C increases with temperature while the ductility reduces. Although this pattern was not clear for NC samples of M44 clay the overall trend suggests strengthening and reduction of ductility. This is apparently in contradiction with the reported reduction in the M value with temperature. It can be explained because the samples in the drained triaxial tests at elevated temperature failed before reaching a critical state. It appears that drained tests may be misleading about the influence of temperature on frictional strength as a result.

The normalized shear modulus of NC samples of M44 clay 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). The overall pattern of normalized secant modulus at 50% shear strain for normally consolidated samples of M44 clay shows that G_{50}/p'_c decreases with increase in temperature during undrained shear tests but remains unchanged for drained shear tests.

The slope of the critical state line in the q - p' plane, M , reduces with temperature rise, while their traces in the v - p' plane are shifted down a certain amount due to increase in temperature. Similar to the INCL, the CSL has the same slope, λ , but is shifted to lower locations in the v - p' plane at higher temperatures. The vertical separation between the INCL and CSL in the v - p' plane slightly reduces when temperature increases, although this might be considered constant for the purpose of modelling.

The results from direct permeability tests on M44 clay at temperatures up to 50°C show firstly that the soil's permeability increases with any increase in temperature because of the reduction in the viscosity of water. Secondly, the relationship between the corrected

permeability (for variation in viscosity and density) and specific volume is linear and independent from temperature changes, and finally that the method of indirect calculation of permeability from the consolidation curve over estimates the result by a factor of approximately two.

6.4 Thermo-Mechanical Modelling of soil

The thermo-elasto-plastic model of Cui et al (2000) was implemented to predict the volumetric changes of M44 clay due to heating. In association with this model, the modified Cam-clay model was also employed for simulation of the stress-strain response of M44 clay.

In addition to critical state parameters of N , Γ , λ , κ , M and μ , Cui et al 's model uses the following parameters: α_0 , T_c , C_1 , C_2 , α_2 , a , k and α_1 which need to be determined for prediction of the thermo-mechanical volume changes of soil. The values of N , Γ , κ and M were found to be temperature dependent but for the purpose of modelling κ was considered to be constant. The thermal overconsolidation effect was assumed to be insignificant for M44 clay implying $k=0$ and $\alpha_1=\lambda$.

Cui et al's model provided reasonable predictions of the thermally induced volume changes for NC and lightly OC (OCR=2.5) samples of M44 clay during drained heating and subsequent cooling. The thermal expansion-contraction behaviour of highly OC samples has been correctly established by this model but the model significantly under predicts the volumetric strain. This model is not capable of predicting thermally induced pore pressure and volume changes during undrained heating. Similar to other known thermo-mechanical models it does not have a mechanism to implement the effects of recent stress history on the thermally induced volume changes reported by Burghignoli et al (2000).

The predictions of modified Cam-clay model (Roscoe and Burland, 1968) using different M values at different temperatures have been satisfactorily within the range of experimental results of drained and undrained shear tests on NC samples of M44 clay indicating lower shear strength at higher temperatures. A reduction in shear strength was not evident during drained shear tests at elevated temperature but the modified Cam-clay predicts the reduction pattern with increase in temperature. Also, the observed reduction in ductility at higher temperatures during drained shear tests could not be

predicted by the Cam-clay model. Similar to NC samples the variations in the undrained shear strength of OC samples at different temperature were predicted but neither the maximum deviator stress reached at failure nor the development of pore pressure were correctly estimated by the Cam-clay model. The observed variations in the stress-strain response of two highly OC samples due to different consolidation histories also could not be predicted by the model.

6.5 Suggestions for future work

The work presented in this dissertation is a small contribution towards a clearer understanding of the complex thermo-mechanical behaviour of soils. It is hoped that the framework, methodology and results reported here will be employed to study other aspects of temperature effects on soil properties which will be useful in developing of a more comprehensive model of soil behaviour at elevated temperature. This section is intended to highlight the recommendations for future research in this area as follows:

- The proximity gauges should be replaced by other displacement measuring devices such as LVDTs or fiber optic gauges. Also the temperature range of the LVDTs are limited to about 100°C while the system is capable of testing at higher temperatures of up to 200°C. Therefore it is suggested that LVDTs with a higher temperature range to be employed.
- A more accurate measurement of temperature can be achieved by using thermistors instead of thermocouples.
- The thermocouple measuring temperature in the centre of sample was found to be unnecessary because its readings were very close to the readings of the base thermocouple and it can cause sample disturbance during mounting.
- It is recommended that the triaxial cell be rebuilt from stainless steel or possibly Pyrex in its middle section in order to: 1) completely eliminate the corrosion, 2) accommodate an internal load cell, additional internal displacement measuring devices and thermistors, 3) provide observations of samples during experiments, 4) allow proper air circulation especially under the cell.
- The system should be provided with a temperature controlled cooling system in order to examine the effects of cooling rate on soil thermal consolidation.

- The recent stress history has been reported to play a major role in the thermal volume changes of OC soils as the observed expansion-contraction behaviour of highly OC samples is replaced only by contraction when the recent stress history is reloading independent from the OCR (Burghignoli et al, 2000). In consequence, planning for thermo-mechanical consolidation tests with the intention to examine the effects of recent stress history on thermally induced volume changes of highly OC samples with different OCRs is highly desirable. Also different stress paths should be considered to explore the effects of thermal yield.
- The current study was mainly focused on undrained shear behaviour of NC and OC samples of M44 clay at elevated temperature and few drained triaxial tests were carried out at elevated temperature. So it is recommended that a set of drained triaxial tests to be performed on NC and OC samples of M44 clay in order to reach a clear pattern for the variations of drained shear strength and stiffness with temperature.
- Due to the limited number of previous experimental data on effects of temperature on shear strength of soil it was not possible to establish a relationship between variations of shear strength with temperature changes and other parameters such as liquid limit and plasticity index. It is expected that more triaxial tests on soils with different Atterberg limits may lead to a correlation between variations in shear strength at elevated temperature and these parameters.
- Direct permeability tests at 75°C and 100°C on M44 clay will lead to a better understanding of temperature effects on permeability, absolute permeability, consolidation and properties of pore water.
- The coefficient of thermal expansion of clay particles should be measured from a proper method (such as XRD, McKinstry 1965) for the purpose of comparison with calculated values from the internal displacement measuring devices.
- The current state of thermo-mechanical modelling, despite the complexity in some cases, is still far from complete. Future developments of thermo-mechanical models should be based on more physically meaningful parameters and more experimental data from different aspects of soil behaviour.

The coefficient of swelling, κ , was found to be dependant on the effective stress level and temperature. Considering this variation and using the concept of critical state might lead to major developments in future thermo-mechanical models.

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