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Impact of Drainage Conditions on Thermal Volume Change of Soft Clay

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ABSTRACT: This study focuses on an evaluation of the thermal volume change of normally-consolidated Kaolinite clay under both undrained and drained conditions. For the tests under either condition, clay specimens were heated in a modified triaxial test setup from room temperature (23 °C) to approximately 60 °C then subsequently cooled. In both tests, the thermal volume change of the clay specimen was inferred using image analysis. During heating, elastic expansion was observed for the undrained specimen while plastic contraction was observed for the drained specimen. The thermally-induced excess pore water pressures measured in the undrained specimen compared well with predicted values from a mechanistic model. However, the thermal volume change of the drained specimen predicted using the pore water pressures measured in the undrained specimen indicated an under-prediction, possibly due to the particular parameters used in the analysis as well as the possibility that thermally-accelerated creep may be superimposed atop thermal consolidation.

INTRODUCTION

A clear understanding for the thermal behavior of soil is needed in many geotechnical engineering applications, such as design of deep repositories of radioactive waste (Gens et al. 2010), energy piles (Brandl 2006; Laloui et al. 2006; Murphy and McCartney 2015), thermal ground improvement (Abuel-Naga et al. 2006) and thermally-active geotechnical systems (Coccia and McCartney 2013; Stewart et al. 2014). These applications have led to increasing considerations of the temperature effects on the engineering properties of soils and have made the thermo-mechanical behavior of soils as one of the major issues in latest geotechnical engineering.

The aim of this research is to study the thermo-mechanical behavior of normally-consolidated Kaolinite clay under temperatures up to approximately 60 °C under different drainage conditions. A laboratory testing program using a modified triaxial test was formulated to evaluate the effect of temperature on the thermally induced pore water pressure generation in undrained conditions and thermally induced volume change in drained conditions. The results from the laboratory tests under different drainage conditions were compared to evaluate whether the drainage of thermally-induced pore water pressure is the main mechanism of thermal volumetric contraction observed in soils (Campanella and Mitchell 1968; Hueckel and Baldi 1990). The volume change during tests with different drainage conditions was also compared with the isotropic compression curve measured for the saturated clay.

PREDICTION OF THERMALLY-INDUCED EXCESS PORE WATER PRESSURE IN SATURATED SOILS

Campanella and Mitchell (1968) developed a theoretical approach to estimate the excess pore water pressure generation in a specimen of saturated soil during undrained heating using the concepts of thermo-elasticity and linear elasticity. Specifically, to ensure compatibility of strains during undrained heating, the sum of the changes in volume of the soil constituents due to changes in both temperature and pressure must equal the sum of the volume changes of the total soil mass during changes in temperature ΔT and pore water pressure Δu. The excess pore water pressure generated by a change in temperature during undrained conditions can be expressed as follows:

$$\Delta u = \frac{n\Delta T(\alpha_s - \alpha_w) + \alpha_{st}\Delta T}{m_v} \qquad (1)$$

where n is the porosity of a saturated soil, α_w is the cubical coefficient of thermal expansion of the pore water (equal to 0.00017 1/°C), α_s is the cubical coefficient of thermal expansion of the mineral solids, ΔT is the change in temperature of the soil, Δu is the change in pore water pressure, α_{st} is the physico-chemical coefficient of structural volume change, and m_v is the coefficient of volume compressibility. The value of α_s does not vary significantly for the tests on different clay minerals reported in the literature, so the value used by Campanella and Mitchell (1968) of 0.000035/°C can be used to analyze the results from other clays. The value of α_w is an order of magnitude greater than α_s, which is one of the primary reasons for the pore water pressure change observed during undrained heating of saturated clays. Regarding the estimation of the value of m_v, Campanella and Mitchell (1968) and Uchaipichat and Khalili (2009) observed that a saturated soil expands along the recompression line during undrained heating. On this basis, the value of m_v can be determined from the isotropic recompression curve $(m_v)_r$ at a given value of mean effective stress, as follows:

$$(m_v)_r = \frac{1}{1+e_0}\frac{\kappa}{p'} \tag{2}$$

where κ is the slope of the isotropic recompression line, e_0 is the initial void ratio, and p' is the mean effective stress.

The physico-chemical coefficient of soil structural volume change, α_{st}, represents the tendency for thermal volume change of soils due to the soil structure and physico-chemical effects, and depends primarily on the soil mineralogy for normally-consolidated clays. Ghaaowd et al. (2015) proposed an empirical relationship between the physico-chemical coefficient of structural volume change and the plasticity index, *PI*, based on the thermally induced pore water pressures measured in 13 normally-consolidated soil specimens from different studies, as follows:

$$\alpha_{st} = 1.0 \times 10^{-4} \cdot e^{-0.014PI} \tag{3}$$

MATERIALS AND SPECIMEN PREPARATION

In this study, commercial Kaolinite clay from M&M Clays Inc., of McIntyre, Georgia was used for the experiment. The geotechnical properties of the clay are summarized in Table 1. As the clay has a liquid limit of 47% and a plasticity index of 19, the clay is classified as CL according to the Unified Soil Classification Scheme (USCS). The clay has a specific gravity of 2.6. The isotropic compression curve is shown in Figure 1. The slopes of the normal compression line (λ) and the recompression line (κ) are equal to 0.1 and 0.016, respectively.

Table 1. Properties of the Kaolinite clay and initial conditions of the specimen used in this study.

Liquid limit	47%
Plastic limit	28%
Plasticity index	19
Specific gravity	2.6
Initial gravimetric water content	31%
Initial void ratio	0.90
Initial porosity	0.47

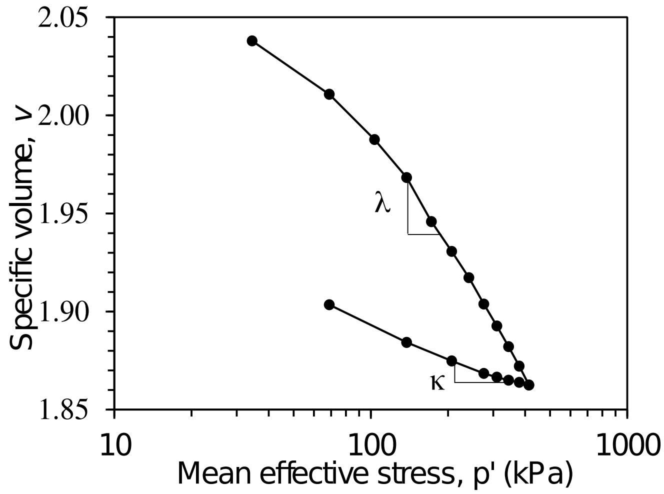

FIG1. Isotropic compression curve for Kaolinite clay.

EXPERIMENTAL METHODOLOGIES

Equipment and procedures

The test was performed by using a modified triaxial system originally developed by Alsherif and McCartney (2013, 2015). A schematic of the system is shown in Figure 2. The cell is comprised of a Pyrex pressure vessel that has the advantage of having low thermal creep behavior while still remaining transparent after repeated heating and cooling cycles. The temperature within the cell is controlled by circulating heated water from a heated water bath through a stainless steel pipe bent into a "U" shape over the specimen. A solar pump is used to circulate the cell water to ensure that it is uniformly mixed, and a thermocouple is used to monitor the cell temperature changes. A pore water pressure transducer is used to monitor the pore water pressure during undrained heating. The cell fluid temperature was monitored using a thermocouple and temperature recorder having a precision of 0.5 °C. The cell pressure and backpressure were controlled using a pressure panel.

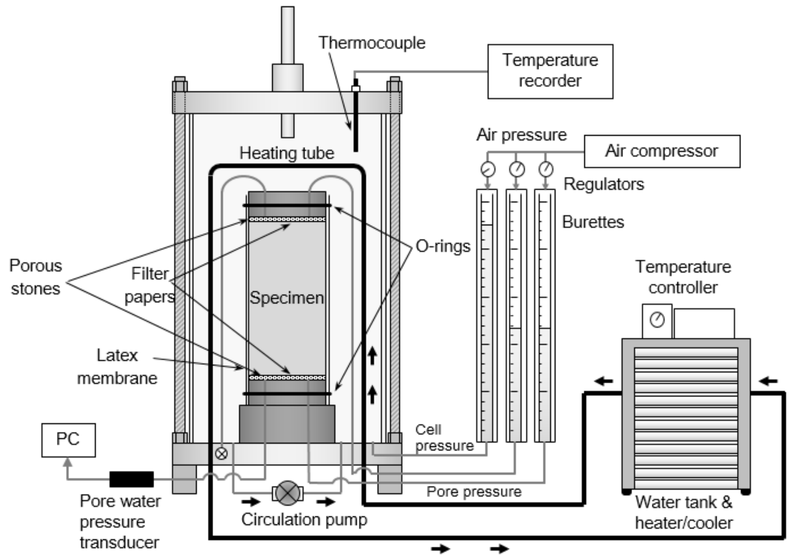

FIG 2. Schematic view of the thermal triaxial system.

The testing procedure first involved back-pressure saturation of the specimen, which was performed by applying the cell pressure and backpressure in stages until reaching a value of Skempton's pore water pressure parameter B of 0.95 while maintaining a constant seating mean effective stress of 21 kPa, then the specimen was consolidated isotropically to a mean effective stress of 276 kPa. During the drained heating test, the drainage valves at the top and bottom of the specimen were kept open, while during the undrained heating test they were all maintained closed except the one leading to the pore water pressure transducer. In both the tests with undrained and drained conditions, the specimens were heated from 23 °C to approximately 60 °C in 5 to 10 °C increments, and each increment was maintained until the pore water pressure or volume change stabilized. Also, during the drained heating test the outflow drainage was also recorded. Images of the specimens were taken using a high resolution camera (model D610 from Nikon) during both the tests to measure changes in volume of the specimen.

RESULTS AND DISCUSSION

Volume change during undrained heating

The thermal volume change of the specimen during undrained heating is shown in Figure 3(a). Despite some nonlinearity in the first stage, the trend between the thermally induced pore water pressure and the temperature is relatively linear. The specific volume of the specimen is shown as a function of the mean effective stress during heating in Figure 3(b). The mean effective stress during heating was calculated as the difference between the initial mean effective stress and the thermally-induced change in pore water pressure. Figure 3(b) also includes the normal compression and recompression curves from Figure 1 for reference. During undrained heating, the specific volume increases with temperature following the elastic recompression curve. These results verify that the value of κ from the recompression curve (κ = 0.02) matches well with the data from the undrained heating test. This confirms the choice of κ in the definition of the physico-chemical coefficient of structural volume change.

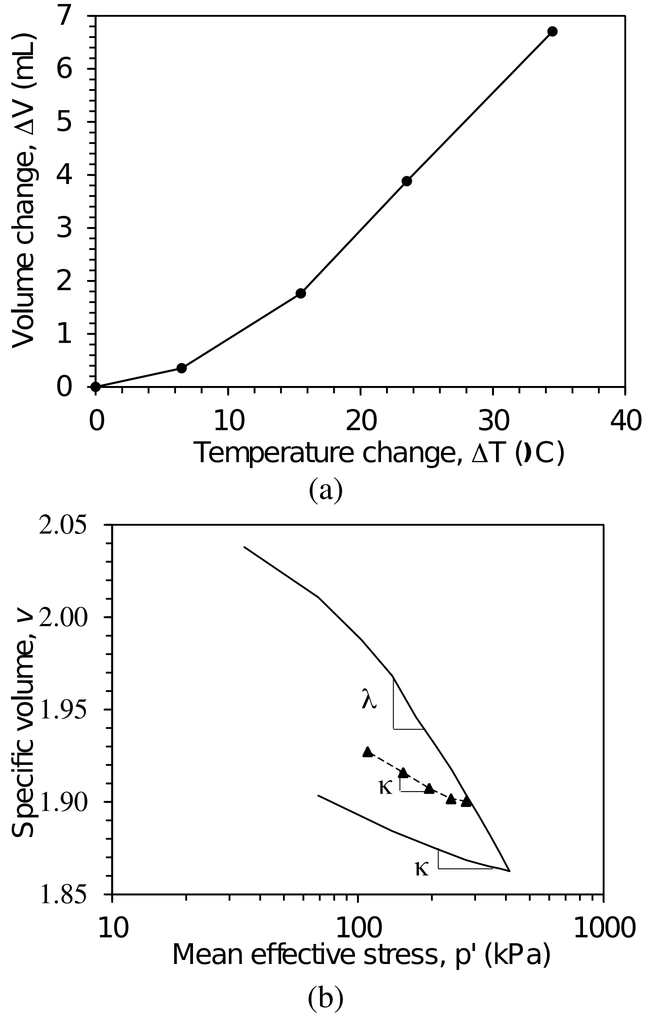

FIG. 3. (a) Volume change versus temperature; (b) Specific volume vs. mean effective stress during undrained heating with comparison to the isotropic compression curve.

Excess pore water pressure generation during undrained heating

The change in pore water pressure as a function of the change in temperature is shown in Figure 4(a). The same data normalized by the initial mean effective stress is shown in Figure 4(b). The thermally induced excess pore water pressure was observed to increase linearly with the change in temperature for the normally consolidated Kaolinite clay.

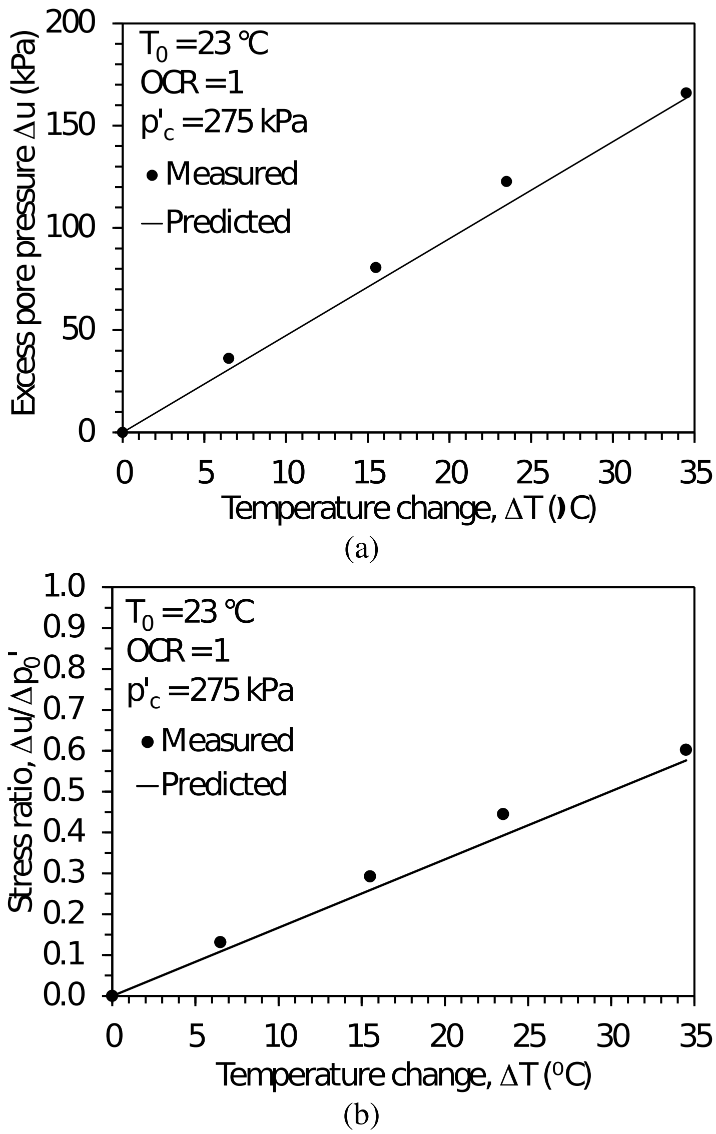

FIG 4. Effect of temperature change on the change in pore water pressure for Kaolinite clay along with the predicted trend from Eq. 1: (a) Pore water pressure; (b) Pore water pressure normalized by the initial mean effective stress

The physico-chemical coefficient (α_{st} = 7.7×10^{-5} 1/°C) was calculated using Equation 3 using the PI of the Kaolinite clay reported in Table 1, which was then used to predict the pore water pressure as a function of temperature using Equation 1. The predicted thermally induced pore water pressures are shown together with the measured values in Figure 4. Good correspondence between the experimental and predicted pore water pressures for the normally-consolidated Kaolinite clay is observed. This observation confirms that the empirical equation of Ghaaowd et al. (2015) can be used to predict soil behavior from index properties, and that the generation of pore water pressure during heating can be estimated from basic properties of the soil constituents and knowledge of the current stress condition. This is useful as it permits the thermally induced excess pore water pressures in undrained conditions to be estimated without having to perform complex experiments.

Volume Change during Drained Heating

The measured volumetric strain of a second specimen of Kaolinite clay during drained heating is shown in Figure 5. The specimen was observed to contract nonlinearly during heating by approximately 1.1%. During cooling, the specimen was observed to partially recover the contraction, indicating that all of the contraction may not have been permanent. This behavior during cooling has been observed in some studies (e.g., Coccia and McCartney 2012), while others have observed additional thermal contraction during cooling (e.g., Uchaipichat and Khalili 2009).

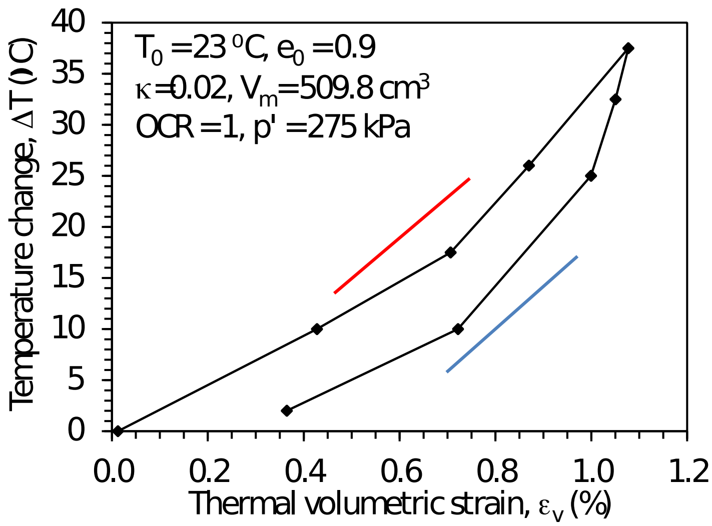

Fig. 5. Volumetric strain under drained heating/cooling cycle of normally consolidated Kaolinite clay.

The volume of water drained from the specimen due to the temperature change $(\Delta V_{\mathrm{DR}})_{\Delta T}$ can be predicted from the measured value of pore water pressure during the undrained test using the following equation developed by Campanella and Mitchell (1968) as shown Figure 5. Even though the drainage is allowed during the drained heating, due to the low permeability of the clay, thermal excess pore water pressure will be generated. This will lead to the decrease in the effective stress, and the volume will not decrease. At the moment the thermal excess pore pressure will dissipate, the effective stress will be recovered, and cause a decrease in volume. The volume change during drainage of these pore water pressures is expected to follow the recompression line, which can be expressed as follows:

$$(\Delta V_{DR})_{\Delta T} = (m_V)_r V_m \Delta p' \qquad (4)$$

where V_{m} is the initial total volume of the specimen (509.87 mL) and $\Delta\pi'$ can be assumed to equal the change in mean effective stress due to the thermally-induced excess pore water pressure Δu. The value of Δu can be estimated as the value measured from an undrained heating test or predicted using the approaches of

Campanella and Mitchell (1968) or Ghaaowd et al. (2015). Accordingly, Equation 4 can be rewritten into the form of the isotropic recompression curve as follows:

$$(\Delta V_{DR})_{\Delta T} = - \frac{1}{1+e_0}\frac{\kappa}{p'}V_m \Delta u \quad (5)$$

This equation signifies the change in volume due to the thermally induced flow of water from the soil, and is expected to be equal to the volume of water flowing out of the specimen during drained heating. In addition to the overall volume change shown in Figure 5, the water drained from the specimen was also measured during the heating process. The measured and predicted volumes of water outflow are shown in Figure 6. The parameters used in the prediction are summarized in the figure. More outflow of water was observed than that predicted using Equation 5. This may indicate that the simple effective stress volume change analysis in Equation 5 may not be sufficient to capture the thermal volume change of saturated soils, and that an analysis that considers thermal creep may be necessary.

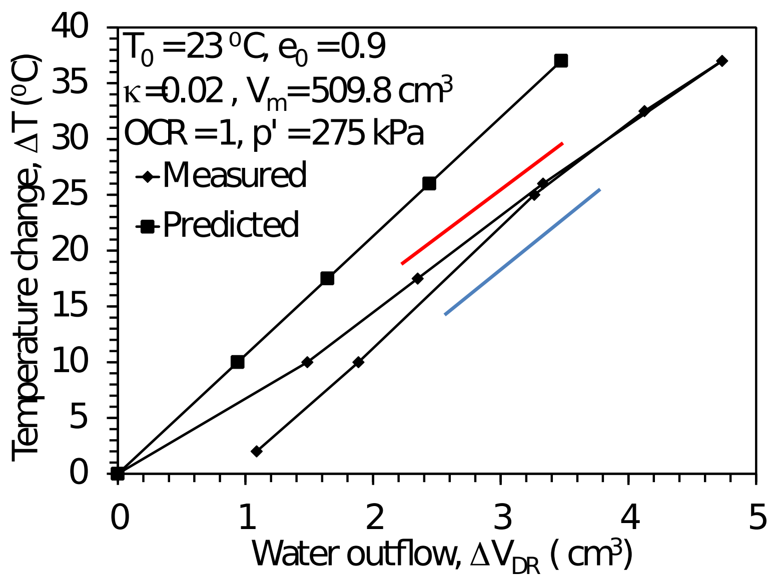

FIG.6. Measured and predicted drained water volume during drained heating.

The overall change in volume of the soil specimen $(\Delta V_{\mathrm{m}})_{\Delta T}$ due to a change in temperature depends both on the volumetric contraction calculated using Equation 6-b which is rearrange of the change in volume of water drained equation as well as the expansion of the different phases, as follows (Campanella and Mitchell 1968):

$$(\Delta V_{DR})_{\Delta T} = \alpha_W V_W \Delta T + \alpha_s V_s \Delta T - (\Delta V_m)_{\Delta T} \quad (6\text{-a})$$

$$(\Delta V_m)_{\Delta T} = \alpha_W V_W \Delta T + \alpha_s V_s \Delta T - (\Delta V_{DR})_{\Delta T} \quad (6\text{-b})$$

where V_{w} is the initial volume of pore water before heating (241.5 mL for the test with

OCR = 1), and V_s is the volume of mineral solids (268.3 mL for the test with OCR = 1). A comparison between the measured volume change of the specimen and the prediction using Equation 6-b is shown in Figure 7. As the temperature is increased, the soil constituents will expand by different values and cause thermal excess pore water pressure generation followed by water drainage, moving and reorientation of the solid particles, and contraction in the soil specimen. The different between the predicted data and the recorded data could be due to the thermal creep which happened after the primary thermal consolidation, or the use of particular parameters in the prediction such as the slope of the recompression line, and cubical coefficient of thermal expansion of the mineral solids.

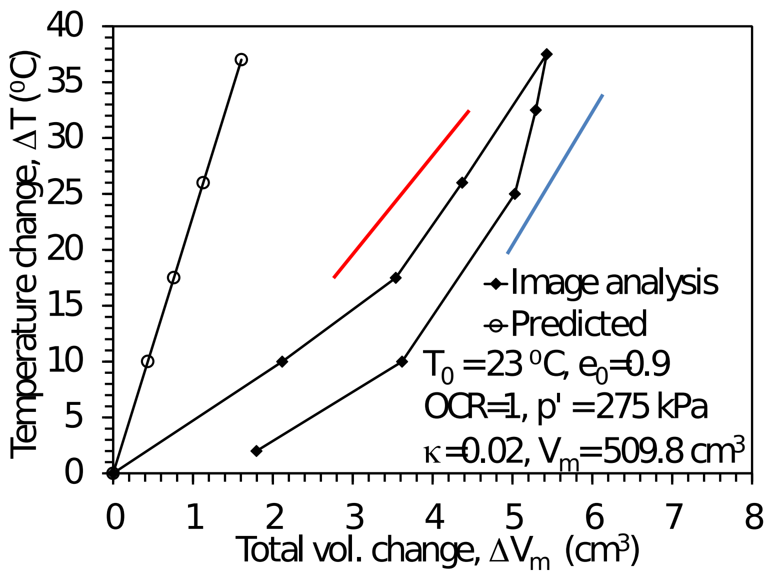

FIG.7. Measured and predicted volume changes for drained heating.

CONCLUSIONS

Drained and undrained heating triaxial tests were performed to evaluate the impact of the drainage on the volume change during the specimen temperature change. The thermally-induced pore water pressures measured during the undrained heating test were found to correspond well with the results from a mechanistic model. The thermally-induced volume expansion during the drained heating test was found to be partially recoverable. When the pore water pressures from the undrained heating test were used to predict the thermally-induced volumetric contraction observed in the drained heating test, an under-prediction was observed. This is possibly due to the particular parameters used in the analysis such as slop of the recompression line , and cubical coefficient of thermal expansion of the mineral solids, but could also be due to thermal creep could be happened right after the thermal consolidation.

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