Effect of Drained Heating and Cooling on the Preconsolidation Stress of Saturated Normally Consolidated Clays

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ABSTRACT

The thermo-mechanical behavior of saturated clays during a heating/cooling cycle is relevant from the perspective of understanding different types of energy geostructures as well as understanding the use of heat for soil improvement. This paper involves a study of the effect of a heating/cooling cycle on the preconsolidation stress of saturated normally consolidated clays. Although many studies have observed a decrease in preconsolidation stress (thermal softening) after heating of overconsolidated soils, fewer studies have investigated changes in preconsolidation stress of normally consolidated soils. Available thermo-elasto-plastic models indicate that a heating-cooling cycle will lead to thermal contraction and an apparent overconsolidation effect for normally consolidated soils (thermal hardening), but inconsistencies in the literature have been observed. This study involves the use of a thermal triaxial cell to first consolidate kaolinite clay to normally consolidated conditions, apply a drained heating or a heating/cooling cycle, followed by mechanical loading to higher mean effective stresses. The tests presented in this study confirm that cooling also induces an apparent overconsolidation effect on the initially normally consolidated clay, but with a preconsolidation stress greater than that expected from the initial virgin consolidation line before heating. The results are a positive finding regarding the possible use of heat to improve the mechanical response of soft clays.

INTRODUCTION

Soft clay deposits pose challenges to geotechnical engineers due to their low shear strength, high compressibility and complex dynamic response. Preconsolidation with surcharge loading and use of vertical drains are widely used methods to enhance the performance of soft clays. A more recent approach to soft soil improvement is in-situ heating by using geothermal heat exchangers embedded in the soft soil deposit.

The effect of temperature on preconsolidation stress of saturated clays has been studied by several researchers (Plum and Esrig 1969; Tidfors and Sallfors 1989; Eriksson 1989; Hueckel and Baldi 1990; Towhata et al. 1993; Boudali et al. 1994; Cui et al. 2000; Sultan et al. 2002; Laloui and Cekerevac 2003; Abuel-Naga et al. 2006, 2007). These studies conclusively show an apparent reduction in preconsolidation stress with increasing temperature for initially over consolidated soil specimens heated to different temperatures and subjected to subsequent loading. Tidfors and Sallfors (1989) observed a linear decrease in preconsolidation stress with increasing temperature based on thermal oedometer tests conducted on 5 different clays at temperatures up to 55 °C. On the other hand, Eriksson (1989) observed a nonlinear decrease in preconsolidation stress with temperature for sulphide clay. Laloui and Cekerevac (2003) expressed this apparent decrease in preconsolidation stress using a logarithmic function and a soil specific material parameter. A typical schematic of how the thermal softening relationship was obtained from heating tests on initially overconsolidated clays is shown in Figure 1(a), and the typical shape of the thermal yield (TY) curve defined from the preconsolidation stress values is shown in Figure 1(b).

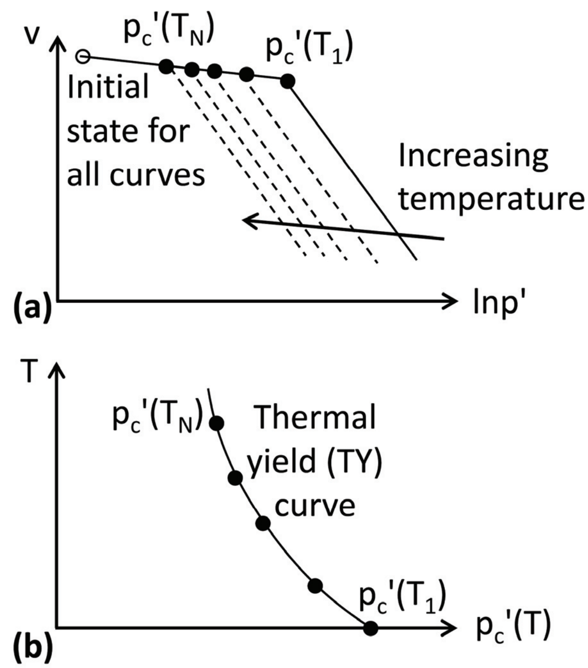

Figure 1. (a) Compression curves on initially overconsolidated soils under different temperatures; (b) TY curve definition

The change in apparent preconsolidation stress with temperature is particularly important in predicting the behavior of normally consolidated soils using thermo-elasto-plastic models. For normally-consolidated soils, the current mean effective stress is equal to the yield stress, so heating will lead to a shift of the TY curve to the right as shown in Figures 2(a) and 2(b). The shape of the TY curve in Figure 2(b) is from Laloui and Cekerevac (2003), but other empirical relationships have been proposed in the literature (e.g., Hueckel and Borsetto 1990; Cui et al. 2000). Heating will also cause the virgin compression line (VCL) to shift to the left by the difference between $p_c'(T_1)$ and $p_c'(T_2)$ on the initial TY curve as shown in Figure 2(c). The shift in the VCL corresponds to plastic contraction expressed in Figure 2(c) as a change in specific volume Δv_T^p. Cooling is expected to lead to elastic contraction Δv_T^e, and mechanical loading after a heating-cooling cycle will result in a hardening effect with yielding when reaching the VCL corresponding to the initial state before heating and cooling. If the soil had been compressed under elevated temperatures (without cooling), the clay is expected to behave in normally consolidated conditions and follow the lower VCL in Figure 2(c).

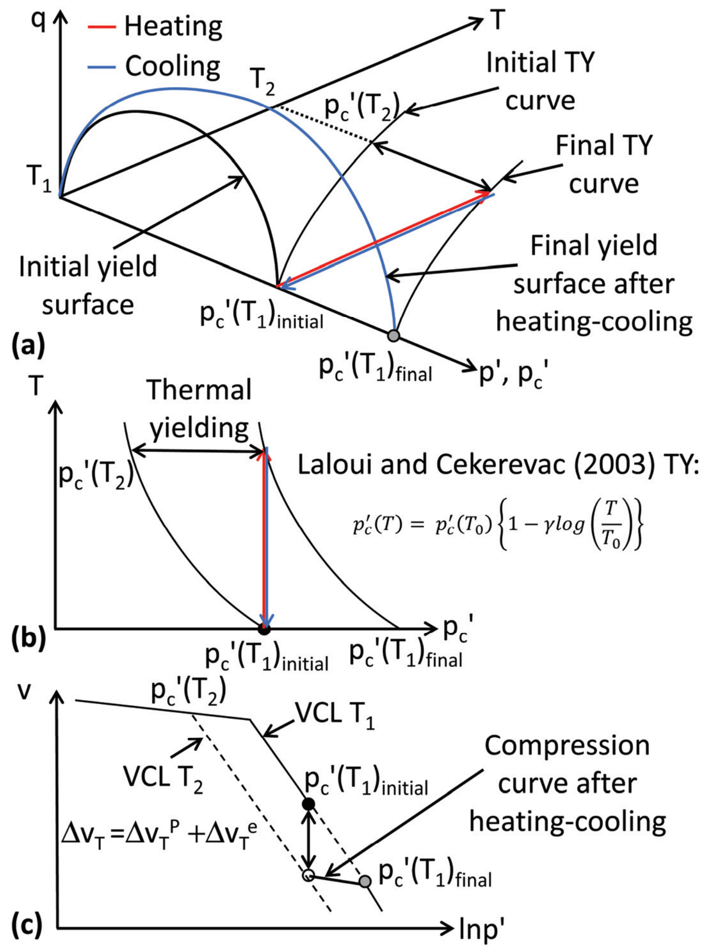

Figure 2. Thermal yielding of normally consolidated clays during heating and cooling: (a) q-p'-T space; (b) Rightward shift in TY curve during heating; (c) Thermal volume change and subsequent compression curve after heating-cooling

An issue is that thermo-elasto-plastic models like that shown schematically in Figure 2 may not capture the behavior of normally consolidated soils after a drained heating-cooling cycle. Upon further loading of a saturated normally consolidated clay subjected to a drained heating-cooling cycle, an apparent overconsolidation state has been observed (Plum and Esrig 1969; Laloui and Cekerevac 2003; Abuel-Naga et al. 2007). Based on the model in Figure 2, it would be expected that the preconsolidation stress would be the value corresponding to the intersection with the virgin compression curve before heating. However, this is not always observed in the literature. The overconsolidated behavior and the shift in the virgin compression line observed by Plum and Esrig

(1969) is shown in Figure 3 for illitic clay heated to 50 °C then cooled to 24 °C. Another example is that Sultan et al. (2002) observed that a higher increase in preconsolidation stress was obtained upon further loading for a heating cooling cycle with a higher change in temperature.

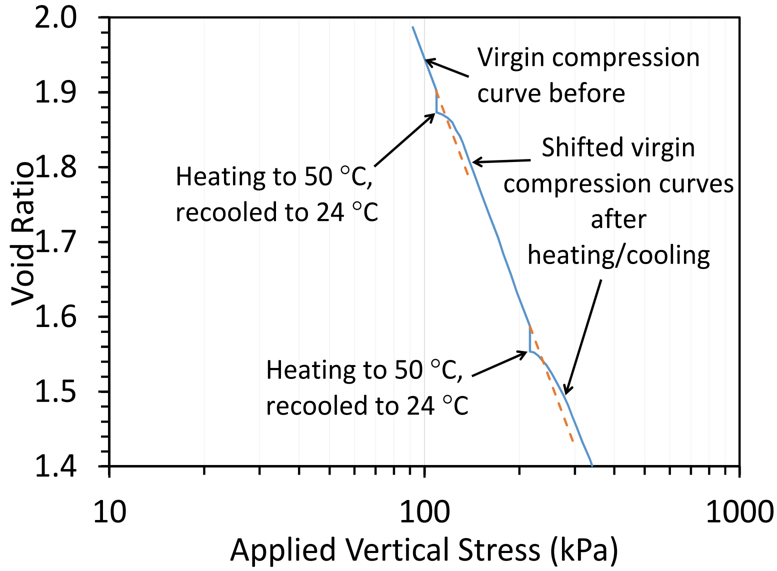

Figure 3. Change in preconsolidation stress after a heating cooling cycle observed by Plum and Esrig (1969)

For illite and Newfield clay samples which were only heated to 50 °C, Plum and Esrig (1969) observed normally consolidated behavior upon further loading. Hueckel and Baldi (1990) and Abuel-Naga et al. (2007) also observed similar behaviour for Pontida clay, Boom clay and Bangkok clay respectively. On the contrary, Towhata et al. (1993) and Sultan et al. (2002) observed an apparent overconsolidation effect upon further loading of a sample only subjected to heating for remolded kaolinite and boom clay respectively.

Several studies in literature found the slope of the virgin compression line to be unaffected by temperature (Finn 1951; Campanella and Mitchell 1968; Plum and Esrig 1969; Laloui and Cekerevac 2003). In contrast, Tanaka et al. (1997) and Sultan et al. (2002) observed a change in the slope of the virgin compression line at different temperatures. These contradicting observations in literature indicated the need for further investigation on the effect of temperature on the preconsolidation stress and compression curve on normally consolidated clays. This study focuses on the results obtained from a triaxial test conducted on a saturated normally consolidated clay subjected to a heating cooling cycle.

MATERIAL AND TEST METHODS

Material. Commercial kaolinite clay obtained from M&M Clays Inc. of McIntyre, GA was used in this study. This clay was also tested by Ghaaowd et al. (2017), Takai et al. (2016) and Samarakoon et al. (2018). Properties of the clay are given in Table 1.

Table 1. Properties of the Kaolinite clay

Parameter	Value
Liquid Limit	47%
Plasticity Index	19
Specific Gravity	2.6
Slope of VCL (λ)	0.09
Slope of RCL (κ)	0.02
USCS Classification	CL

Experimental Set-up. The laboratory test was performed using a modified triaxial system developed by Alsherif and McCartney (2015). A schematic of the system is shown in Figure 4. The system comprised of a Pyrex pressure vessel having low thermal creep behavior. A stainless steel, U-shaped pipe was placed inside the cell and heated water was circulated using a heated water bath to control the temperature inside the cell. To ensure uniform mixing, a pump capable of withstanding high fluid pressures and temperatures was used to circulate the cell water. A pore water pressure transducer was used to measure the changes in pore water pressure during heating and cooling. The cell fluid temperature was measured using a thermocouple and a temperature recorder to a 0.5 °C accuracy. The cell pressure was applied using a flow pump and the back-pressure was controlled using a pressure panel.

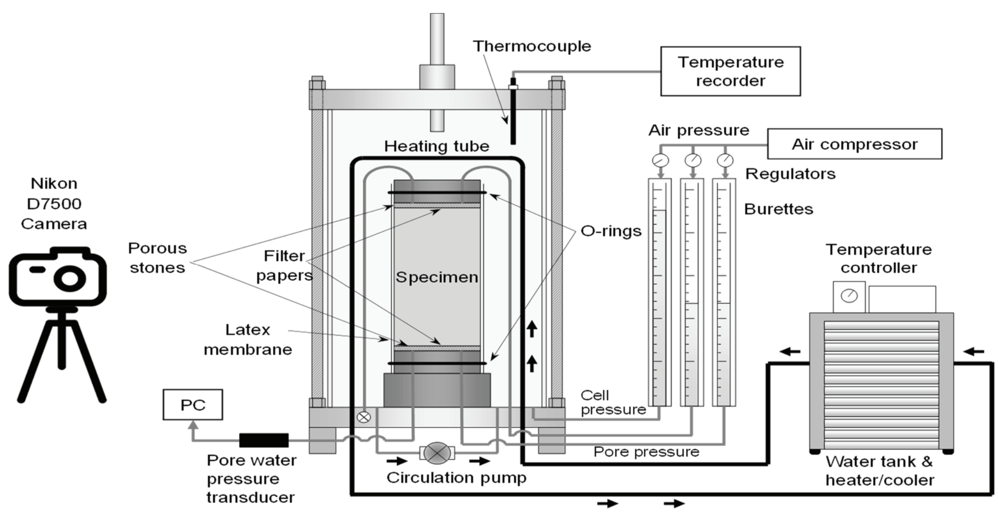

Figure 4. Thermal triaxial set-up

In addition to monitoring the drainage from the specimen during consolidation, heating and cooling, images of the specimen were taken using a high-resolution camera (Nikon D7500) during the test to measure changes in volume using an approach similar to Uchaipichat et al. (2011). The sample volume was considering to be made up of a series of stacked disks where the height of a single disk was one vertical pixel and the diameter was the number of horizontal pixels. Macari et al. (1997) found the relationship between the observed and true radius to be linear using a simplified two dimensional model which maps the specimen to the image plane. This approximation is more applicable when the distance between the camera and the specimen is large compared to the specimen height. Based on this approximation, the magnification effects due to the cell and cell fluid were accounted for by using the actual specimen volume measured at the beginning of the test.

Procedure. For preparation of the specimen, clay powder was first mixed with deionized water in a mixer to form a slurry with a water content of 130%. The slurry was then poured into a steel hollow cylinder having a diameter of 88.9 mm. Porous stones and filter paper were placed on the top and bottom of the slurry. The slurry was consolidated using a compression frame at a constant rate of 0.04mm/min for 48 hours. Then it was subjected to constant vertical stresses of 26, 52, 103 and 181 kPa in 24 hour-long increments.

The sedimented clay layer was then extracted and trimmed to a smaller cylindrical specimen with diameter of 72.4 mm suitable for testing in the thermal triaxial cell. The specimen was back-pressure saturated until the Skempton's pore water pressure parameter B value was at least 0.95. The initial void ratio of the specimen was 1.05. It was then isotropically consolidated following loading, unloading and reloading paths to a final mean effective stress of 248 kPa. The specimen is at normally consolidated conditions at this stress state. While maintaining the normally consolidated stress state, the specimen was subjected to drained heating where the temperature was increased from 23 °C to 59.5 °C in 5 increments (about 7 °C per increment). Each increment was maintained for about 4-5 hours until the volume change stabilized. Then the specimen was cooled back to room temperature in a similar manner. Following a heating cooling cycle, the specimen was isotropically loaded in increments up to a mean effective stress of 310 kPa. The thermo-mechanical path for the test procedure is shown in Figure 5.

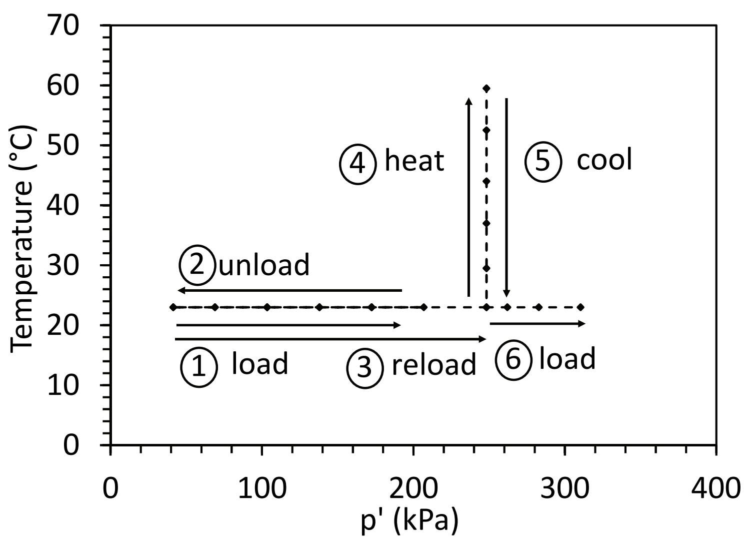

Figure 5. Thermo-mechanical path evaluated in the thermal triaxial test

EXPERIMENTAL RESULTS AND DISCUSSION

The change in void ratio of the specimen during heating and cooling is shown in Figure 6(a) along with the corresponding temperature profile. A decrease in void ratio is observed during heating whereas an increase in void ratio is observed during subsequent cooling. However, the net effect on the specimen was a reduction in void ratio after a heating cooling cycle. The change in volumetric strain with temperature is shown in Figure 6(b). The increase in void ratio during cooling is not in agreement with the general trend observed in literature where elastic contraction is observed during cooling. (Baldi et al. 1991; Sultan et al. 2002; Abuel-Naga et al. 2006) However, Plum and Esrig (1969) and Hueckel and Baldi (1990) observed a slight expansion during drained cooling for illitic clay and Pontida clay respectively.

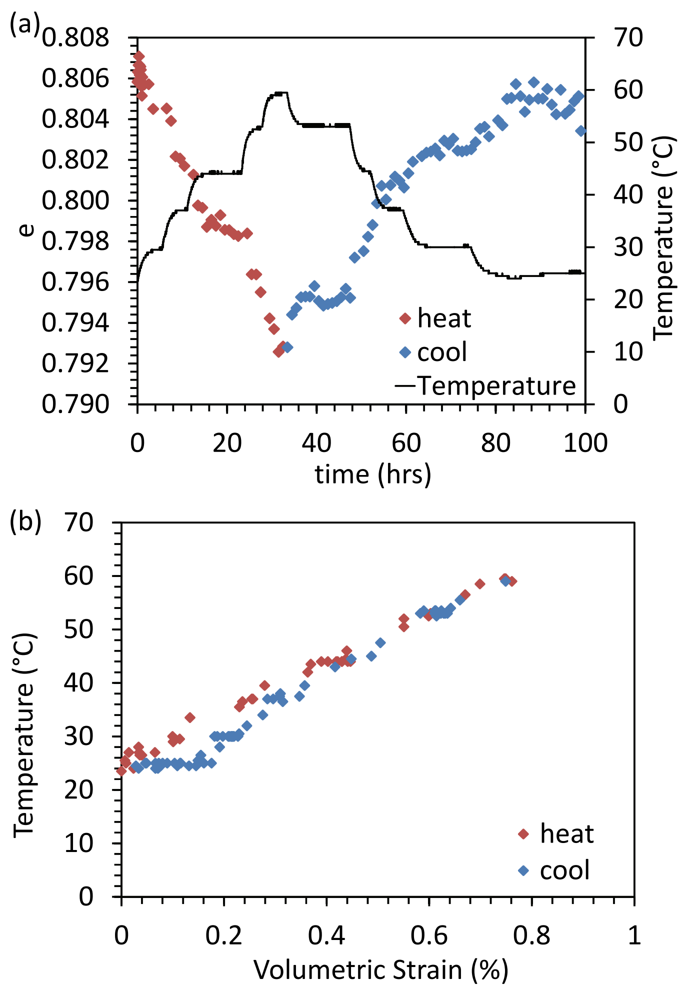

Figure 6. (a) Volume change of the specimen during drained heating and cooling; (b) Change in thermal volumetric strain with temperature

The change in excess pore water pressure during the heating-cooling cycle is shown in Figure 7. The change in excess pore water pressure is observed to be between ±4.5 kPa. Based on the observations, the change in excess pore water pressure generated during incremental heating and cooling under drained conditions can be considered negligible. This indicates that the thermal volume change process can be assumed to be drained during the entire heating and cooling process.

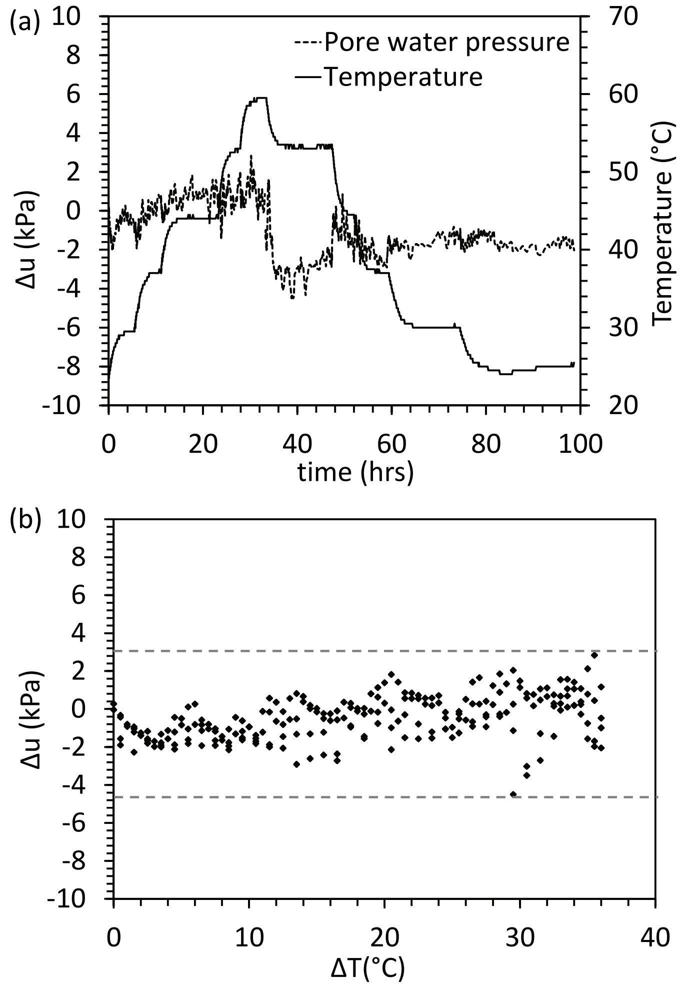

Figure 7. (a) Excess pore water pressure during heating and cooling; (b) Variation of excess pore water pressure with temperature

The compression curve for the specimen is shown in Figure 8 in the e vs ln(p') plane. It can be observed that the specimen which was initially at a normally consolidated state showed overconsolidated behavior after being subjected to a heating cooling cycle. The slope in the compression curve immediately after a heating cooling cycle is similar to that of the recompression index (κ) of the clay. Upon further loading the specimen regains a normally consolidated state at a higher mean effective stress than before. The slope in this section is similar to that of the virgin compression index (λ) with a shift in the curve to the right. The new preconsolidation stress was estimated to be around 290 kPa which results in an increase of 42 kPa due to a heating cooling cycle. This conforms to the thermal hardening phenomenon described in literature where a soil specimen experiences a hardening effect merely due to a temperature change without any additional mechanical loading.

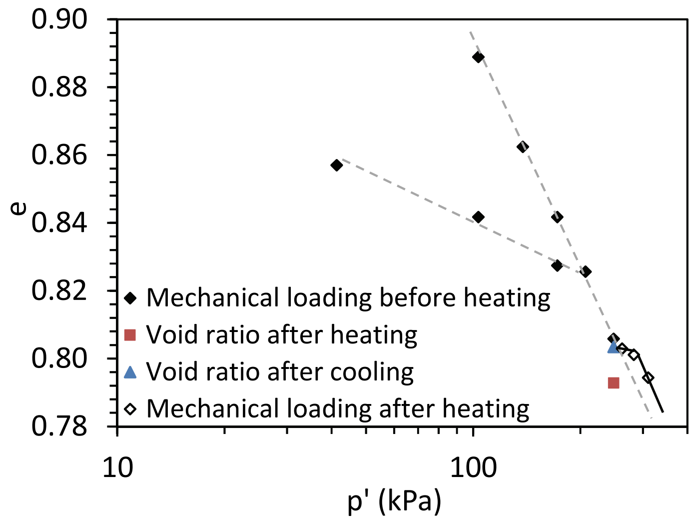

Figure 8. Compression curve for thermo-mechanical loading showing the shift in the virgin compression curve after the heating-cooling cycle

CONCLUSION

The results presented in this study indicate a normally consolidated clay subjected to a heating cooling cycle will observe an increase in its preconsolidation stress upon further loading. This increase is attributed to the thermal hardening phenomenon that the soil undergoes due to a heating cooling cycle. A displacement of the virgin compression line was observed where it shifted to the right with a similar slope after a heating cooling cycle. The clay specimen which was at a normally consolidated state prior to being subjected to a heating cooling cycle, behaved as an overconsolidated clay during subsequent loading with a slope similar to that of the recompression index. After reaching its new preconsolidation stress, a normally consolidated behavior could be observed again. The results indicate the possibility of using in-situ heating with geothermal heat exchangers as a means of improving soft soils to induce a hardening effect.

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