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# Impact of drained heating and cooling on undrained shear strength of normally consolidated clay

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**This study focuses on the effects of a heating-cooling cycle on the undrained shear strength of normally consolidated clay specimens. A clear increase in undrained shear strength was observed for specimens sheared after drained heating to an elevated temperature, while a further increase in undrained shear strength was observed for specimens sheared after a drained heating-cooling cycle. This is attributed to the permanent decrease in volume during drained heating followed by the elastic decrease in volume during drained cooling. The initial mean effective stress was also observed to play an important role in the magnitude of the increase in undrained shear strength, with greater increases observed for normally consolidated specimens with lower mean effective stresses.**

## Introduction

The impact of temperature on the shear strength of clays has been widely studied since the 1960's and several constitutive relationships have been developed to consider the impacts of stress history and drainage conditions (Laloui et al. 2015). General observations from the literature include: (1) temperature changes are not expected to affect the friction angle of clays (defined at peak or critical state conditions), (2) the undrained shear strength is dependent on the pore water pressure during shearing, the initial effective stress, and the void ratio; and (3) the drainage conditions during heating will lead to different trends in the shear strength. Shearing after undrained heating typically leads to a decrease in undrained shear strength associated with the increase in excess pore water pressures (and decrease in mean effective stress) during undrained heating, while shearing after drained heating leads to an increase in undrained shear strength for normally consolidated clays due to a reduction in void ratio during drained heating. One situation that has not been fully studied is shearing of normally consolidated clays after a drained heating-cooling cycle, such as that experienced by the soil surrounding a thermal drain system (Abuel-Naga et al. 2006). It is expected that plastic contraction will occur during drained heating, followed by elastic contraction during drained cooling. This implies that after cooling, specimens will have a slightly lower void ratio and should have a greater undrained shear strength than that observed during shearing after drained heating. However, it is not clear if the change in temperature will lead to a transition in the magnitude of excess pore water pressure during undrained shearing. This study focuses on results from triaxial compression tests on saturated normally consolidated clay following different temperature paths and drainage conditions.

## Methods

### *Materials*

Kaolinite clay obtained from M&M Clays Inc. of McIntyre, GA was used in this study. 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. The clay has a specific gravity of 2.6, and the slopes of the normal compression line ($\lambda$) and recompression line ($\kappa$) are 0.100 and 0.016, respectively. The excess pore water pressure during undrained heating of this clay was characterized by Ghaaowd et al. (2015), while the volume change during drained heating was characterized by Takai et al. (2016).

### *Experimental Setup*

The nonisothermal triaxial compression tests were performed using the thermal triaxial system developed by Alsherif and McCartney (2015) that was further adapted for testing saturated clays by Takai et al. (2016). A schematic of the system is shown in Figure 1. The cell is comprised of a Pyrex pressure vessel exhibiting low thermal creep while remaining transparent after repeated heating and cooling cycles. The temperature within the cell is controlled by circulating heated water from a temperature-controlled circulating bath through a stainless-steel pipe bent into a “U” shape over the specimen. A pump able to accommodate high fluid temperatures and pressures is used to circulate the cell water to ensure that it is uniformly mixed. The cell fluid temperature was monitored using a thermocouple and temperature recorder having a precision of 0.5 °C. The cell pressure and specimen backpressure were controlled using a pressure panel, and a temperature-corrected pore water pressure transducer was used to measure changes in pore water pressure during undrained heating and shearing. In addition to monitoring the drainage from the specimen during consolidation and drained heating and cooling, images of the specimens were taken using a high-resolution camera (model D610 from Nikon) during the tests to measure changes in volume using the approach of Uchaipichat et al. (2011).

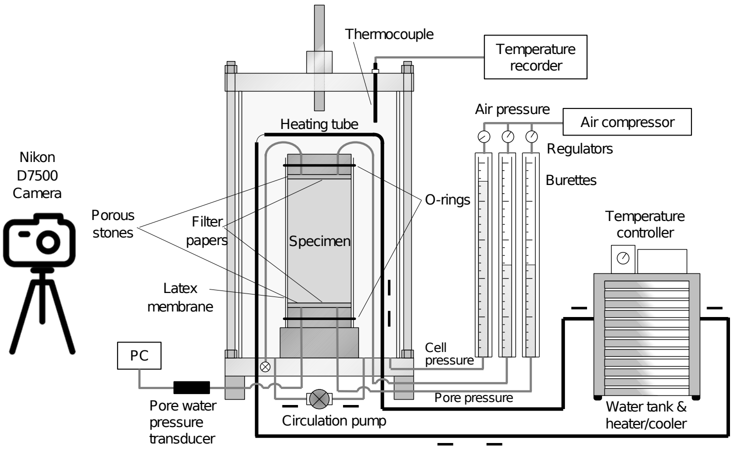


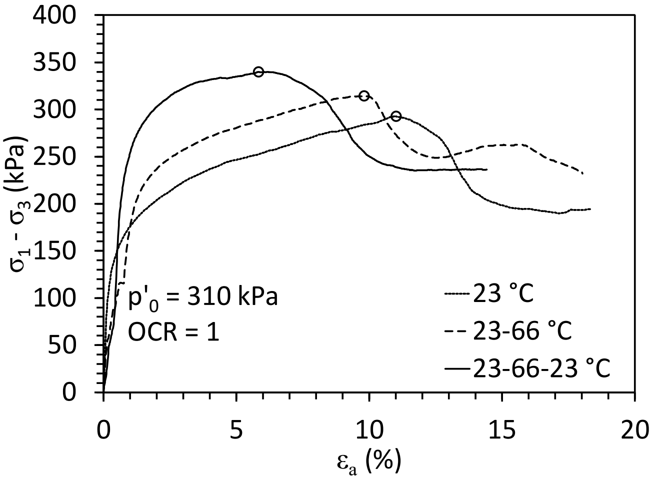
**Fig. 1: Thermal triaxial setup**

## *Procedures*

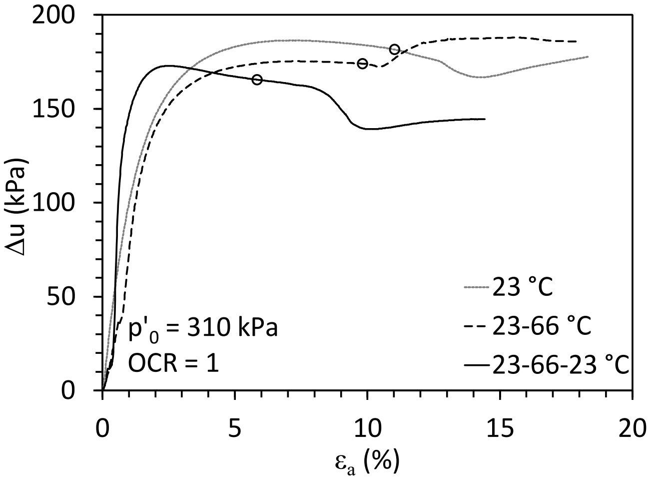
The clay specimens were prepared from sedimentation using an approach described by Ghaaowd et al. (2015), and trimmed specimens were backpressure-saturated in the thermal triaxial cell, which involved applying the cell pressure and backpressure in stages until reaching a value of Skempton's pore water pressure parameter B of at least 0.95. The specimens were then consolidated isotropically to a desired mean effective stress. Some specimens were sheared in undrained conditions at room temperature conditions to provide a baseline case for comparison. For the specimens tested at different temperatures, the drainage valves at the top and bottom of the specimen were kept open during heating and cooling. Another set of specimens were heated from 23 °C to 66 °C at a relatively fast rate (0.2 °C/min) after which the elevated temperature was maintained until the volume change stabilized, after which the specimens were sheared in undrained conditions. The last set of specimens were heated from 23 °C to 66 °C in drained conditions, then cooled back to 23 °C before shearing in undrained conditions.

## Results and discussion

The principal stress difference versus axial strain results from three consolidated undrained triaxial compression tests conducted at a mean effective stress of 310 kPa following three different temperature paths are shown in Figure 2. The OCR of 1.0 refers to the initial state of the specimen where it was normally consolidated prior to the application of any mechanical or thermal loading. An increase in the maximum principal stress difference can be observed for the specimen sheared after drained heating to 66 °C, and a further increase in undrained shear strength is observed for the specimens sheared after drained heating to 66 °C followed by drained cooling back to 23 °C. The shapes of the stress-strain curves for the three tests were relatively similar despite different peak values. The corresponding reductions in the excess pore water pressure for each of the three tests are shown in Figure 2(b). Although the magnitude of excess pore water pressure was similar in all three tests, all three specimens showed positive strains during shearing as expected for normally consolidated specimens. The effective stress paths for the three tests are shown in Figure 3. An interesting observation is that the maximum principal stress values fall onto the same peak failure envelope



(a)



(b)

**Fig. 2: Examples of consolidated undrained triaxial compression test results for the saturated clay following different temperature paths (points denote the maximum principal stress): (a) maximum principal stress difference vs. axial strain (b) excess pore water pressure vs. axial strain**

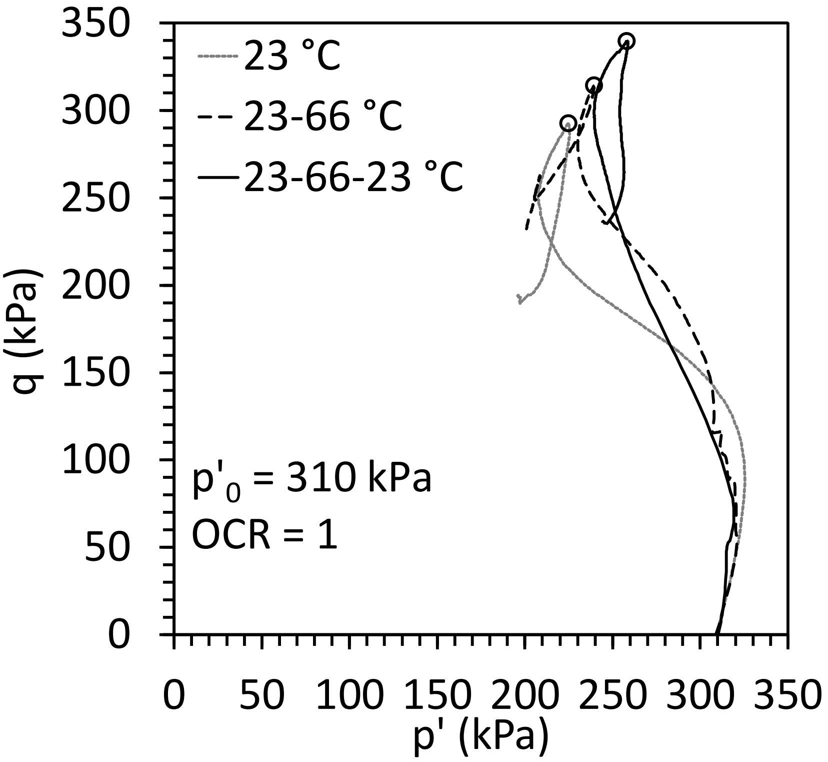


**Fig. 3: Examples of effective stress paths for the saturated clay following different temperature paths**

The results from tests performed at other initial mean effective stresses are shown in Figure 4. Like the observation drawn from the effective stress paths in Figure 3, the results in Figure 4 indicate that the specimens following different temperature paths tested at different initial mean effective stresses all fall onto the same peak failure envelope. The slope shown in Figure 4 of 1.29 is not equal to the slope of the critical state line but corresponds to the slope of the peak failure envelope. Assuming that the maximum principal stress differences from each of the tests corresponds to the undrained shear strength of the soil, the trends in the undrained shear strength for specimens sheared under room temperature conditions, after heating, and after a heating-cooling cycle are shown in Figure 5(a). A clear increase in undrained shear strength after a heating-cooling cycle is observed. The percent increase in undrained shear strength following a heating-cooling cycle is appreciable, and ranges from 16 to 54%. The percent increase in undrained shear strength was observed to decrease as the initial mean effective stress increased, which is counterintuitive to the trends in the thermally induced excess pore water pressures during undrained heating observed by Ghaaowd et al. (2015). Specifically, it was observed that greater changes in excess pore water pressure are observed for specimens with higher initial mean effective stress. The final void ratio values of specimens sheared at room temperature, after heating and after a heating-cooling cycle are shown in Figure 5(b). It can be observed that the void ratio decreases when the specimen is subjected to drained heating and even further after a drained heating-cooling cycle, conforming to the corresponding increase in undrained shear strength.

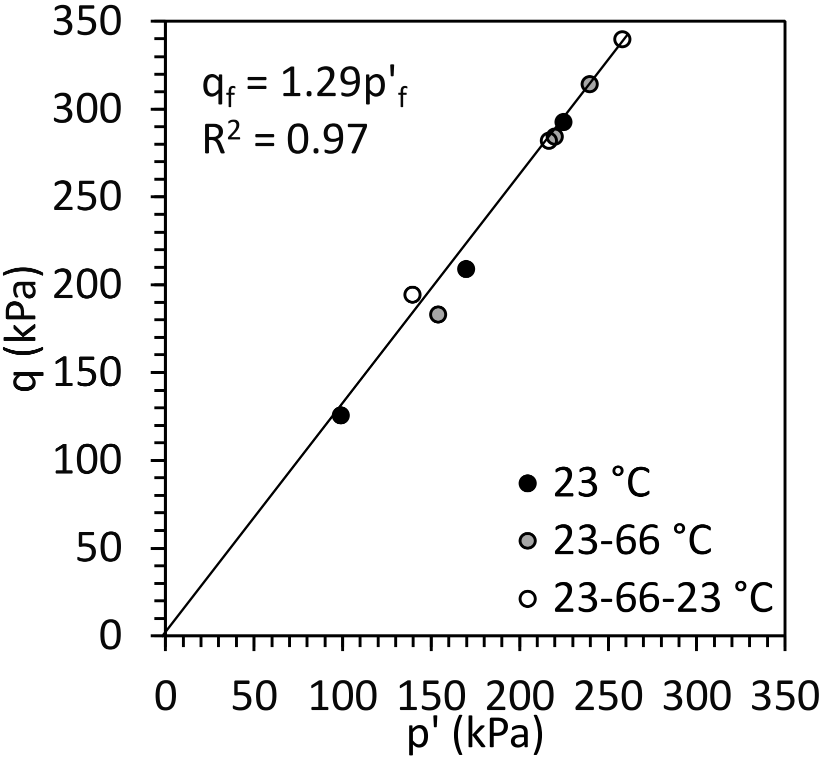
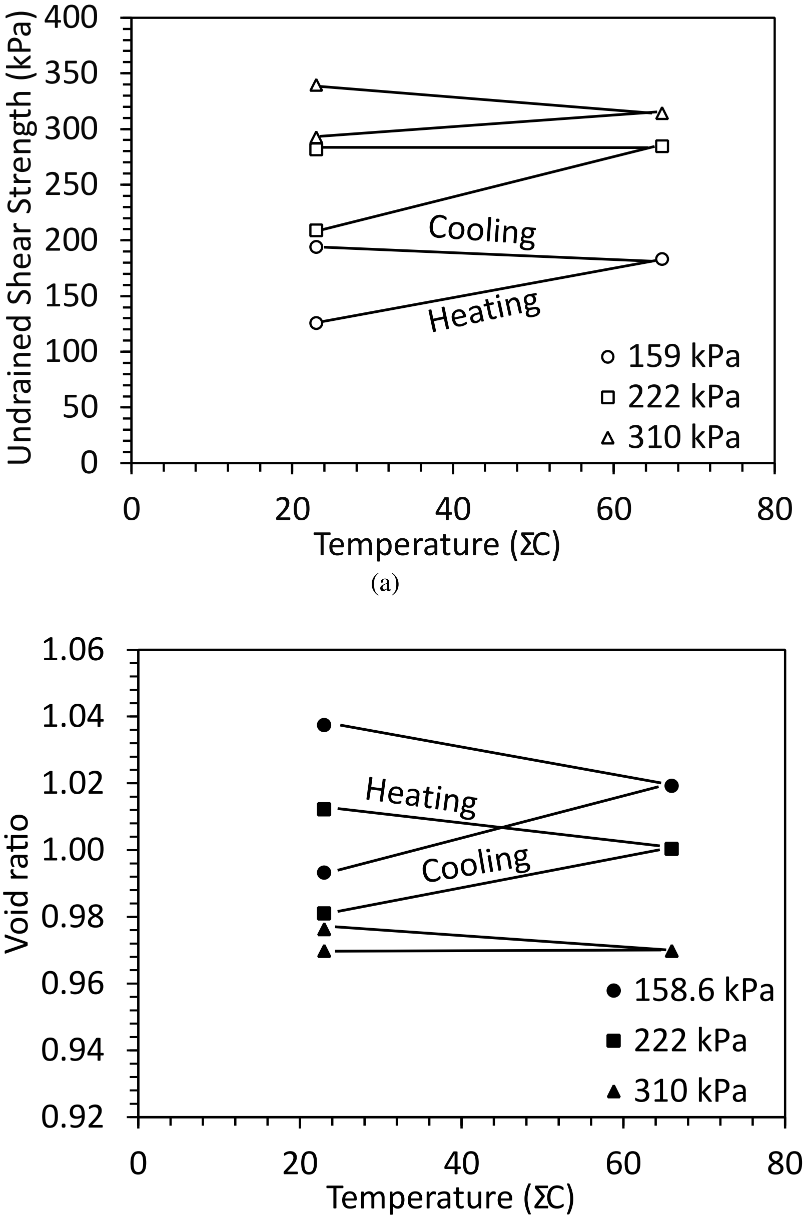


**Fig. 4: Maximum principal stress differences for specimens sheared at room temperature, after heating, and after a heating cooling cycle versus the mean effective stress at failure**



(a)

(b)

**Fig. 5 (a) Undrained shear strength at different mean effective stresses for specimens sheared at room temperature, after heating, and after a heating**

**cooling cycle; (b) Final void ratio at different mean effective stresses for specimens sheared at room temperature, after heating and after a heating cooling cycle**

## Conclusions

The results presented in this study indicate that the impact of a heating-cooling cycle such as that used in a thermal improvement application (i.e., thermal drains) will have a positive effect on the undrained shear strength of normally consolidated clays. This trend in undrained shear strength is attributed to the plastic decrease in volume during drained heating combined with the elastic decrease in volume during drained cooling. It was observed that this positive effect was greater for specimens tested at lower initial mean effective stresses. Despite the clear effects of temperature on the undrained shear strength, the changes in temperature were not observed to affect the slope of the peak failure envelope, which is consistent with previous studies on the effects of temperature on the shear strength of clays.

## Acknowledgements

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