Undrained Shear Strength and Consolidation Behaviour of Kaolinite at Elevated Temperatures

Thomas Ring[1], Chin Leo[2], Samanthika Liyanapathirana[3], and Qinghua Zeng[4]

[1]PhD Candidate, Western Sydney University, Sydney, NSW, Australia
[2]Professor, Western Sydney University, Sydney, NSW, Australia
[3]Associate Professor, Western Sydney University, Sydney, NSW, Australia
[4]Senior Lecturer, Western Sydney University, Sydney, NSW, Australia
Corresponding author's E-mail: t.ring@westernsydney.edu.au

Abstract

Modern engineering solutions which exhibit a change in the natural ground temperature require a better understanding of the fundamental behaviour of soils with respect to temperature. Examples include; energy piles, nuclear storage, and novel construction techniques such as freezing or heating. A temperature change can affect soil settlement/volume, as well as its strength characteristics. The response is complex, a function of numerous factors including; material type/composition, stress history, drainage condition, loading, and time. This paper presents results from triaxial tests performed on reconstituted kaolinite using multiple stress histories to investigate the impact of temperature on consolidation behaviour and undrained shear strength.

Keywords: Kaolinite, Triaxial, Consolidation, Temperature

1. INTRODUCTION

The interest of thermal effects on mechanical properties of clays has increased as applications have necessitated a better understanding. Several scenarios can alter the natural thermal state, such as; nuclear waste disposal, landfills, or energy geostructures. One method under consideration for nuclear waste disposal is burying it deep within a large clay deposit. As the nuclear material degrades, it continues to generate heat. Landfills can also generate heat as the waste decomposes and chemical reactions occur. Energy piles act as heat exchangers between the building and soil. In addition, future methods can be developed, which capitalize on any changes in behaviour such as heated wick drains.

A number of studies are available, which provide some understanding of the thermal impacts. Materials and test procedures vary between these studies; this can create challenges trying to interpret results. In particular, a change in stress history and drainage conditions during heating can produce adverse results.

This paper presents the findings of six triaxial tests performed on normally consolidated kaolinite at a range of temperatures. Three tests had a single shearing stage, while the remaining three had multiple shearing stages allowing for additional consolidation and critical state information to be obtained from a single sample.

1. MATERIAL, EQUIPMENT, AND EXPERIMENTAL PROCEDURE

1.1. Material

A commercially produced product ‘Clay Ceram’ was used for this study. It is mined from a natural clay deposit, then ground and sold as a dried powder. X-ray diffraction yielded mineralogy of 68% kaolinite and 32% quartz. A liquid limit of 45.5% and a plastic limit of 30.0% were determined.

Samples of 50 mm diameter were prepared by making a slurry, mixed at double the liquid limit. Once mixed, a vacuum of up to -100 kPa was applied along with agitation to assist in removing the entrapped air bubbles produced during mixing. The slurry was then poured into a lightly greased mould, 200 mm in height. Pressure was applied using static loading and drainage allowed via top and bottom porous stones. The load was gradually increased until a pressure of 100 kPa was achieved. The maximum load was maintained for a minimum of 24 hours before the sample was removed and trimmed to 100 mm in height.

1.2. Equipment

A GDS High Pressure Environmental Triaxial System (HPETAS) was used for the testing. The HPETAS is comprised of a 50 kN load frame, 20 MPa cell with thermal pads, 2 MPa 1000 cc pressure controller, 2 MPa 200cc pressure controller, 3 kN internal load cell, temperature controller unit, three internal temperature sensors, and a data acquisition system.

1.3. Experimental Procedure

Triaxial tests were performed on specimens with either a single shearing stage or multiple shearing stages stopping at the maximum deviator stress before consolidating at a higher pressure and then shearing again. A total of three single shearing specimens and three multiple stage specimens are presented. The naming convention of each sample was stress history (NC for normally consolidated), effective consolidation pressure in kPa (all shearing stages listed), test temperature and unit (ie. 20C). Therefore, specimen NC/200/400/800/45C was normally consolidated at pressures of 200, 400, and 800 kPa each with a shearing stage and all conducted at a temperature of 45 ^{o}C. Exact test sequence is outlined below:

Single shearing stage

- B check (min 95%).
- Isotropic consolidation to 200 kPa effective, with a back pressure of 50 kPa until pore water pressure (PWP) within 5 kPa of back pressure.
- Undrained heating to desired temperature for 4 hours to allow PWP to stabilize.
- Maintain temperature and allow drainage for 4 hours to dissipate PWP.
- Undrained shearing at a rate of 0.0333 mm/min (approx. 2%/hr) until 15% strain.

Multi shearing stages

- Same initial steps as the single shearing with the final step terminating once the maximum deviator stress is reached which is taken as less than 1 kPa change over 0.25 mm vertical displacement.

- Isotropic consolidation to 400 kPa effective, with a back pressure of 50 kPa. Until pore water pressure within 5 kPa of back pressure.
- Undrained shearing at a rate of 0.0333 mm/min (approx. 2%/hr) until maximum deviator stress is reached (less than 1 kPa change over 0.25 mm vertical displacement).
- Isotropic consolidation to 800 kPa effective, with a back pressure of 50 kPa. Until pore water pressure within 5 kPa of back pressure.
- Undrained shearing at a rate of 0.0333 mm/min (approx. 2%/hr) until maximum deviator stress is reached (less than 1 kPa change over 0.25 mm vertical displacement).

2. MAIN RESULTS AND DISCUSSION

The peak (maximum) deviator stress for all tests is summarized in Table 1. Overall, there is a clear increase in the maximum applied stress with an increase in temperature. Initially, heating was applied with the drainage path closed, allowing monitoring of the pore water pressure. It was observed that an increase in temperature generated excess pressure. The larger the temperature increase, the larger the excess pore water pressure. After the excess pressure peaked or stabilized, the drainage path was opened allowing it to dissipate (and reduce the void ratio) before the shearing shear stage.

Table 1: Triaxial Results

Specimen	Peak Deviator (kPa)
NC/200/27C	183.6
NC/200/46C	196.3
NC/200/61C	221.8
NC/200/400/800/26C	170.2 / 358.0 / 745.0
NC/200/400/800/47C	186.2 / 388.5 / 771.2
NC/200/400/800/62C	207.9 / 408.8 / 771.6

Along with an increase in the peak deviator stress, a stiffening of the specimen can be seen in Figure 1, as evidenced by the higher principal stress at a lower strain. An increase in the elastic modulus and peak deviator stress was also noted by Cekerevac and Laloui (2004) performing triaxial tests on reconstituted kaolinite at elevated temperature.

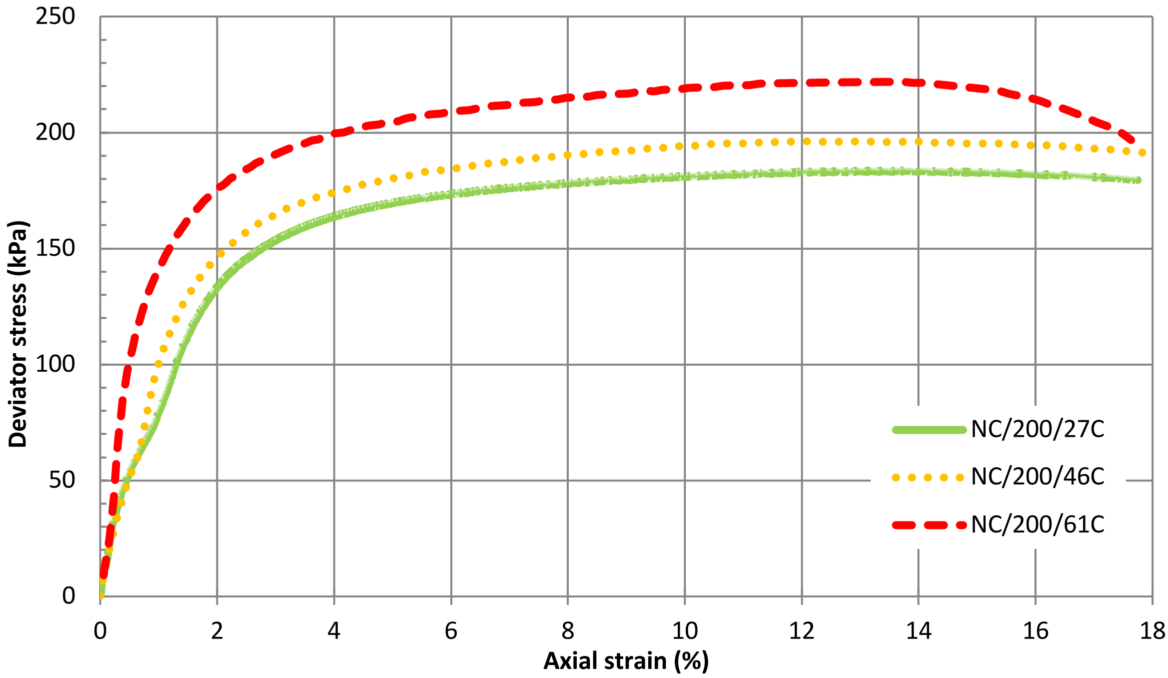

Figure 1: Single shearing stage triaxial tests

The three specimens, which were sheared past their critical state are presented in Figure 2, using the Cambridge stress path plane, with parameters defined in Equations 1 and 2. The stress path is indicative of normally consolidated or slightly overconsolidated behaviour.

$$q = \sigma_1 - \sigma_3 \quad (1)$$

$$p' = (\sigma'_1 + 2\sigma'_3)/3 \quad (2)$$

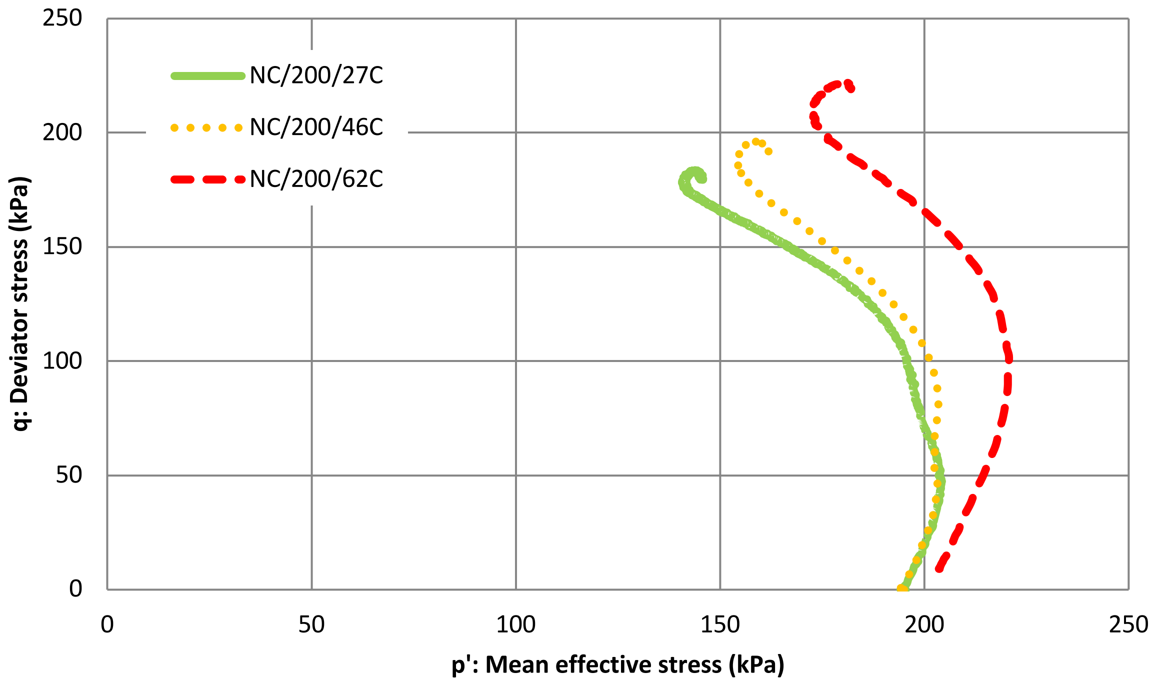

Figure 2: Single shearing stage mean effective stress vs. deviator

The critical state line appears to be slightly changed with temperature as shown in Figure 3. The slope of the critical state line is 1.10, with a corresponding drained friction angle of 27.7 degrees. There is some ambiguity regarding any relationship between temperature and the slope of the critical state line in the literature. It has been postulated by Hueckel, et al. (2009) that it is material specific. This same article presents undrained triaxial test results on over consolidated and normally consolidated reconstituted kaolinite by Cekerevac and Laloui (2004) that show a clear increase in the slope of the critical state line, although the original paper did not. The relationship is explained in greater depth in the most recent publication, therefore the initial representation and interpretation may have been incomplete. A smaller program using 'Todi clay' which has a mixed mineralogy of montmorillonite, illite, and kaolinite, by Burghignoli, et al. (2000) did not show any relation.

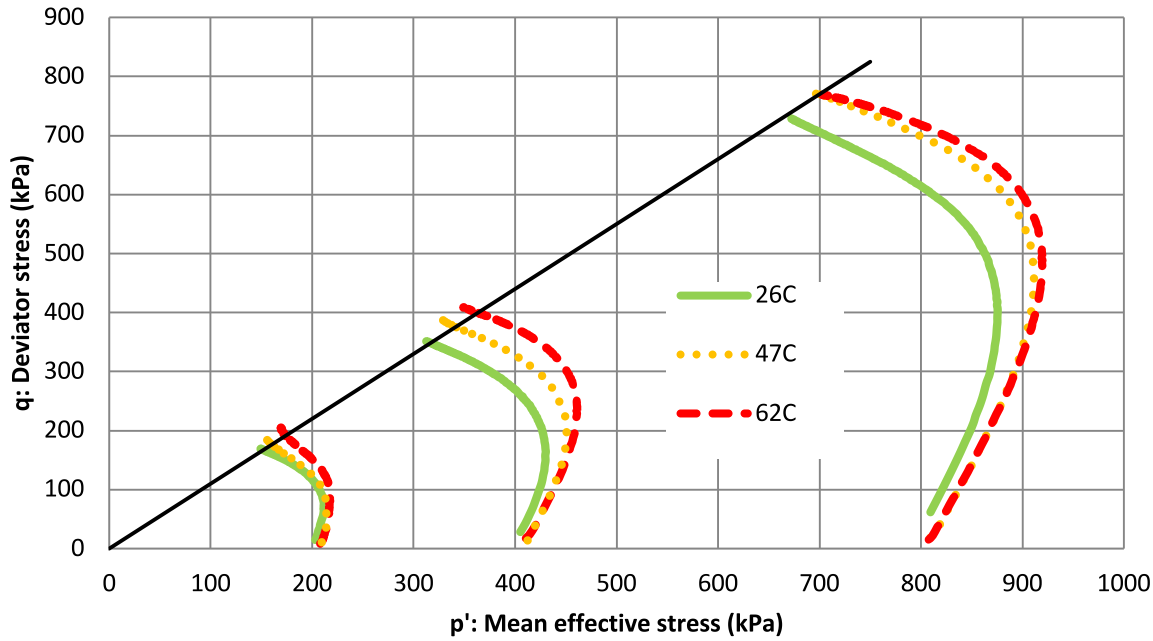

Figure 3: Multi shearing stage mean effective stress vs. deviator

After the first and second shearing stages, the specimens were consolidated at higher effective pressures (twice the previous amount). The consolidation rate was calculated using the log time method for each of these pressure steps. As shown in Table 2 and Figure 4, there is a clear trend of increased consolidation rate with an increase of temperature. Previous published work using the same material and one dimensional consolidation yielded similar results, Ring, et al. (2016).

Table 2: Consolidation Rate (m^2/yr)

Pressure Step (kPa)	27°C	47°C	62°C
200-400	23.9	28.6	38.6
400-800	26.0	33.2	38.6

BS 1377 Part 5 provides a temperature correction factor for one dimensional consolidation tests although only between 0 and 40°C and it was intended for comparisons only and not to correct for in situ temperatures. The correction factor appears to be derived directly from the relationship between the viscosity of water and temperature as given by Korson, et al. (1969). Using the change in viscosity with temperature, there is a reasonable correlation to the rates found here. Delage, et al. (2000) conducted tests on Boom clay and found little increase in the consolidation rate once temperatures were above 70°C, while Abuel-Naga, et al. (2005) used Bangkok clay tested at temperatures up to 90°C and found a continued increase in consolidation rate.

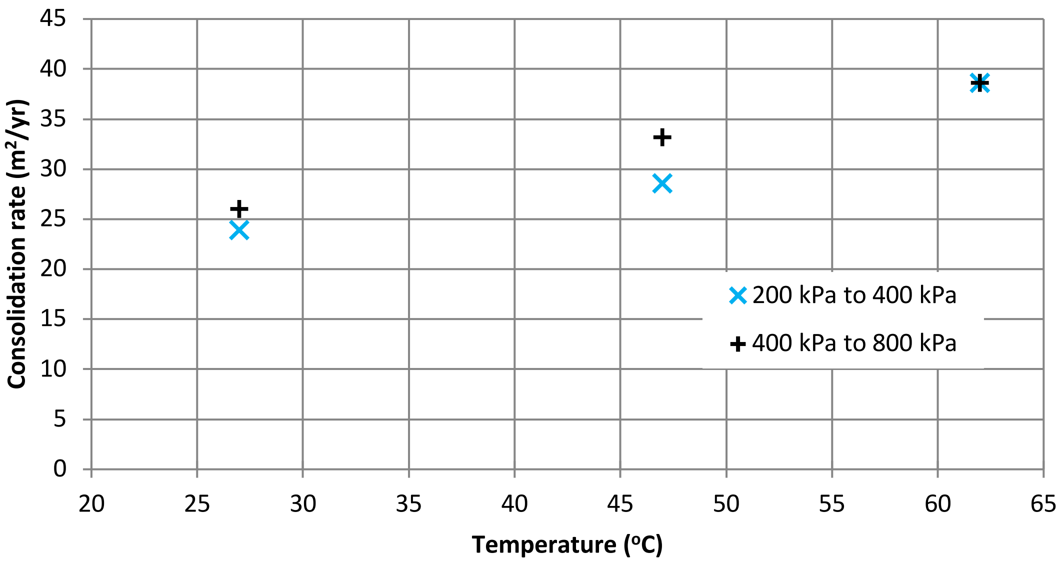

Figure 4: Consolidation rates at different pressure steps and temperatures

3. CONCLUSIONS

Based on the undrained triaxial tests summarized in this paper, the following conclusions are made for normally consolidated kaolinite between the temperatures of 27°C and 62°C:

- The peak deviator stress increases as the temperature increases for the same confining stress.
- There are no significant changes in the slope of the critical state line with an increase in temperature.
- The consolidation rate increases as the temperature increases.

REFERENCES

Abuel-Naga HM, Bergado DT, Rujivipat S, Soralump P (2005). Thermal consolidation of soft Bangkok clay, Lowland Technology International, 7, 13-21

Burghignoli A, Desideri A, Miliziano S (2000). A laboratory study on the thermomechanical behaviour of clayey soils, Canadian Geotechnical Journal, 37, 764-780

Cekerevac C, Laloui L (2004). Experimental study of thermal effects on the mechanical behaviour of a clay, International Journal for Numerical and Analytical Methods in Geomechanics, 28, 209-228

Delage P, Sultan N, Cui YJ (2000). On the thermal consolidation of Boom clay, Canadian Geotechnical Journal, 37, 343-354

Hueckel T, Francois B, Laloui L (2009). Explaining thermal failure in saturated clays, Geotechnique, 59, 197-212

Korson L, Drost-Hansen W, Millero FJ (1969). Viscosity of water at various temperatures, Journal of Physical Chemistry, 73, 34-39

Ring T, Leo C, Liyanapathirana S (2016). Behaviour of kaolinite and bentonite at elevated and lowered temperatures, Taylor & Francis, 271-275