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Authors
Huancollo, Hiden Jaime Machaca
Saboya, Fernando
Tibana, Sérgio
et al.

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Thermal triaxial tests to evaluate improvement of soft marine clay through thermal consolidation

Hiden Jaime Machaca Huancollo[1], Fernando Saboya Jr.[2], Sérgio Tibana[3], John Scott McCartney[4], Ricardo Garske Borges[5]

1 Formerly MSc Student – State University of Norte Fluminense Darcy Ribeiro – UENF Department of Civil Engineering, Rio de Janeiro, Brazil, geomachaca@gmail.com

2 Professor - State University of Norte Fluminense Darcy Ribeiro – UENF, Department of Civil Engineering, Av. Alberto Lamego 2000 - CCT, Campos Rio de Janeiro, Brazil, CEP 28016-812, Tel +(55)22-27397369, saboya@uenf.br. ORCID **0000-0001-9063-5090**

3 Professor - State University of Norte Fluminense Darcy Ribeiro – UENF, Department of Civil Engineering, Rio de Janeiro, Brazil, stibana@gmail.com. ORCID **0000-0002-9425-8461**

4 Professor and Department Chair - University of California San Diego, Department of Structural Engineering. 9500 Gilman Dr. La Jolla, CA, USA, Tele-fax: +001-858-534-9630, mccartney@ucsd.edu. ORCID 0000-0003-2109-0378

5 Civil Engineer - Petrobras CENPES, Research and Development Center, Rio de Janeiro, Brazil, garske@petrobras.com.br. ORCID **0000-0001-7623-0337**

ABSTRACT

This paper presents an experimental study on the thermo-mechanical behavior of marine clay from the Santos Basin off the coast of Brazil. The aim of the study is to assess the gain in undrained shear strength of reconstituted, normally consolidated clay specimens after drained thermal consolidation using a thermal triaxial device. The motivation behind performing these tests is that relatively few studies in the literature have focused on understanding the changes in shear strength of normally consolidated clays after a heating-cooling cycle, a path encountered in using heat to improve the properties of soft clays. Further, the high plasticity marine clays evaluated in this study have a pronounced thermal creep different from that observed in previous nonisothermal tests on clays. Isotropic, consolidated undrained (CIU) triaxial compression tests were performed on specimens consolidated to effective stresses of 100, 200 and 400 kPa then sheared conventionally at room temperature as well as after drained heating-cooling cycles with maximum temperatures of 40 and 55 ºC. The results were analyzed according to critical state soil mechanics after drained thermal consolidation, which was well suited to explain the improvement in undrained shear strength. The results have potential implications on the development of techniques that can promote thermal improvement of deep-water offshore anchors installed in soft soil.

Keywords: Thermal consolidation, thermal creep, shear strength, marine clay.

INTRODUCTION

Early studies on the effects of temperature on soil properties from the 1960's focused on understanding sampling effects associated with extracting soils from the cold subsurface to the warm ground surface and the impacts of buried electrical cables (e.g., Campanella & Mitchell 1968, Plum & Esrig 1969). These studies led to a basic understanding of undrained thermal loading and drained thermal consolidation, as well as establishing the temperature effects on soil properties like the compression indices and strength envelope. With the popularization of nuclear energy, concerns arose regarding encapsulation of radioactive waste in low permeability clays reactivated the interest in understanding the influence of temperature on the mechanical properties of both soft and compacted soils (e.g., Houston *et al.* 1985; Hueckel & Baldi 1990; De Bruyn & Thimus 1996; Delage *et al.* 2000). In recent years, geotechnical studies have focused on the mechanical behavior and thermal response of buried energy geostructures under elevated temperatures, with thermal piles being the most popular (e.g., Brandl 2006; Laloui *et al.* 2006; Bourne-Webb *et al.* 2009, Laloui *et al.* 2014). Several recent studies have found that the heating and cooling operations of thermal piles may have effects on the thermo-mechanical behavior of the surrounding soil, which, in turn, can influence the mechanisms of soil-structure interaction or axial capacity of the thermal pile (e.g., Ng et al. 2014, 2021; Goode & McCartney 2015; McCartney & Murphy 2017; Ghaaowd & McCartney 2018, Ghaaowd et al. 2018, 2021; Yazdani *et al*. 2019a, 2019b, 2021).

To explain the phenomena observed in different applications mentioned above, several fundamental experimental studies have investigated the effects in the mechanical properties of soils under variation in temperature on saturated soils with different stress histories (e.g., Houston *et al.* 1985; Hueckel & Baldi 1990; Kuntiwattanakul *et al.* 1995; Burghignoli *et al.* 2000; Cekerevac & Laloui 2004; Cekerevac & Laloui 2010; Bai *et al.* 2014; Di Donna & Laloui 2015; Vryzas *et al.* 2017; Samarakoon *et al.* 2018; Samarakoon & McCartney 2020; Rotta Loria & Coulibaly 2021). Some few studies are focused specifically on unsaturated conditions (Uchaipichat & Khalili 2009; Coccia & McCartney 2016). The volume change of fine-grained soils due to heating, has been carefully studied and the results have built a strong basis for the development of constitutive models that describe the thermal volumetric strains (e.g., Cui *et al.* 2000; Laloui & Francois 2009; Di Donna & Laloui 2015; Coccia & McCartney 2016; Hong *et al.* 2016; Hong *et al.* 2013, Zhou & Ng 2018; Cheng *et al.* 2020). The mechanisms of volume change under heating from these studies, which include both thermal consolidation and thermal creep have helped explain the effects of stress history, degree of saturation, viscosity, and other variables (Abuel-Naga *et al.*, 2007a; Graham *et al.* 2001; Hueckel *et al.* 2009; Tsutsumi and Tanaka 2012; Coccia & McCartney 2016; Li et al. 2018; Rotta Loria & Coulibaly 2021; Zeinali and Abdelaziz 2021). Most past studies in the literature focused predominantly on overconsolidated soils (often with a single normally consolidated specimen for comparison), and usually focus on the shear strength of soils under elevated temperatures, with only a few focused on understanding the change in shear strength after a heating-cooling cycle (Samarakoon et al. 2018; Jaradat and Abdelaziz 2019). Accordingly, a goal of this study is to better understand the behavior of normally consolidated clays after a heating-cooling cycle in a similar manner as shown by Abuel-Naga *et al*. (2007b).

Despite the wealth of data generated in the aforementioned studies, heating of soils with the goal of modifying their behavior has not been fully explored in engineering practice in the face of its great potential as a soil improvement technique. While there are many soil improvement techniques used in geotechnical practice, ranging from chemical additives, installation of mechanical inclusions such as stone columns, application of a surcharge with vertical drains, to compaction, these techniques are best suited for onshore situations and cannot be readily applied to soft soils under the sea floor in deep water environments. In this scenario, thermal consolidation may be an attractive alternative for offshore industry. Thermal consolidation has been successfully deployed for soil improvement using geothermal heat exchangers (Bergenstahl et al. 1994), thermal drains (Abuel-Naga et al. 2006; Pothiraksanon et al. 2010; Artidteang et al. 2011; Salager et al. 2012; Salager *et al*. 2010), and thermal piles (Ghaaowd et al. 2018, 2021; Ghaaowd & McCartney 2018) in saturated soil deposits. However, questions remain regarding predictions of the change in undrained shear strength after a heating-cooling cycle, especially those related to the mechanical response after thermal consolidation.

Herein, a set of thermal triaxial tests was carried out on remolded marine clay specimens from southern of Brazil to quantify the impact of thermal consolidation and thermal creep associated with a heating-cooling cycle with the goal of understanding the improvement in shear strength response under undrained shearing. This new understanding will help establish a geotechnical approach based on thermal triaxial testing to quantify the expected thermal improvement associated with enhancing the staying capacity of offshore anchors like torpedo piles, which are extensively used in Brazil for anchoring heavy floating oil exploration platforms in deep waters. The test results were interpreted considering the critical state soil mechanics framework with the aid of thermal consolidation modeling approaches.

BACKGROUND

Studies on normally consolidated clays employing thermal oedometer and triaxial tests by Campanella & Mitchell (1968), Plum & Esrig (1969), Burghignoli *et al.* (2000), and Laloui & Cekerevac (2003) observed that additional volumetric strains on the order of 1-2% can be encountered when heating normally consolidated (NC) clayey soil specimens under constant mechanical loading to temperatures of approximately 60-80 °C. Primary thermal consolidation is the result of compression caused by the dissipation of thermally induced pore pressures, along with secondary thermal consolidation resulting from the compression due to the rearrangement of interparticle forces and fabric structural changes at elevated temperature. Campanella & Mitchell (1968) predicted changes in total volume ($(\Delta V_m)_{\Delta T}$) and pore water pressure (Δu) caused by an increase in temperature using the coefficients of thermal expansion of minerals and water and the coefficient of compressibility m_v of the soil skeleton. As for the compression index (C_c) and recompression index (C_e) deduced from oedometer tests in the *log* $(\sigma_v) \times e$ plane and the well-known parameters λ and k in the $ln(p) \times e$ plane, authors such as Campanella & Mitchell (1968), Plum and Esrig (1969), Burghignoli *et al.* (2000) and Laloui

& Cekerevac (2003) observed that they are independent of temperature for heated-cooled specimens.

Several studies have noted that the stress history can play an important role in thermal volume change. For over-consolidated (OC) soils, Baldi *et al.* (1988) found that a rise in temperature has a thermal-elastic effect (dilation) and that slightly overconsolidated and normally consolidated (NC) soils tend to present a contractive behavior with irreversible volumetric strains. The latter feature is important for thermal improvement, where the soils under the seabed are expected to be normally consolidated. In the case of a soil specimen subjected to more than one heating-cooling cycle, Campanella & Mitchell (1968), Vega & McCartney (2015), Di Donna & Laloui (2015), Burghignoli & Desideri (1988) and Plum & Esrig (1969) concluded that the effects on volume change is more pronounced during the first heating, because, after cooling the soil tends to exhibit over-consolidated behavior and a stiffer response. Studies like Jaradat and Abdelaziz (2019) noted the importance of controlling the rate of cooling in addition to the rate of heating.

When a normally consolidated saturated clay is heated under constant isotropic effective stress in undrained conditions, differential expansion of the pore water and soil solids leads to excess pore water pressures. If drainage is allowed, these excess pore water pressures will dissipate resulting in a time-dependent volume change Campanella & Mitchell (1968). This is referred to as thermal consolidation, and theories for the time dependency have been developed (e.g., Zeinali & Abdelaziz 2021). Houston *et al.* (1985) found that the higher the increase in temperature, the greater the excess pore water pressure generated during undrained heating, which may decrease the effective stress to the point of shear failure.

To account for the thermal volume change of soils with different stress histories, several thermo-elastoplastic models have been proposed. Hueckel & Baldi (1990) and Laloui & François (2009) proposed thermoplastic models for normally and over consolidated saturated clays. Cui *et al.* (2000) have developed a dedicated thermo-elastoplastic model, while Graham *et al.* (2001) and Abuel-Naga *et al.* (2009) proposed a modified Cam-Clay model considering the effects of temperature. Coccia & McCartney (2016) presented an alternative constitutive model using the secondary compression to model the thermal volumetric change where the water viscosity at different temperatures plays an important role in this process. They noted that the thermal volume change is associated with the prior mechanical loading path through thermally accelerated creep, and that an overconsolidated clay may show thermal expansion or contraction depending on whether it was previously loaded or unloaded. Most of these approaches indicate that both thermal consolidation and thermal creep mechanisms may come into play during thermal volume changes.

Drainage of thermally induced excess pore water pressures (primary thermal consolidation) and thermal creep (secondary thermal consolidation) lead to a densification of normally consolidated clays and an increase in undrained shear strength, which is the main goal of thermal improvement. Some of the studies whose objective was to assess the influence of temperature on the shear strength of clays are summarized in Table 1. Most of the authors observed a rise in shear strength in normally consolidated (NC) clays heated under drained (D) and sheared in undrained conditions. In the case of over-consolidated (OC) clays, some authors in Table 1 stated that shear strength is not strongly dependent of the temperature. Houston *et al.* (1985) performed undrained triaxial tests at temperatures of up to 180 °C and found that the thermal consolidation of soils leads to an enhancement in undrained shear strength like that obtained from mechanical consolidation. Burghignoli *et al.* (2000) studied the influence of thermal history on shear strength using triaxial tests, denominating "normally heated" (NH) for specimens that were never exposed to temperatures above the current temperature and "overheated" (OH) for specimens subjected to temperatures above the current temperature. The authors reported that the peak deviatoric stress of OH specimens are an average of 10% higher than those of NH. This change seems to indicate that thermal history may have an influence on the critical state line of clays. However, authors such as Houston *et al.* (1985), Abuel-Naga *et al.* (2007a), Cekerevac *et al.* (2005) and Hamidi *et al.* (2017) concluded that the slope of the critical state line is independent of temperature. On the other hand, Abuel-Naga *et al.* (2007a) indicated that this may not always be the case for natural soils due to difficulty in obtaining identical undisturbed subsoil samples.

Abuel-Naga *et al.* (2007a) and Cekerevac *et al.* (2005) observed that the ratio between volumetric and shear plastic strain ($d\varepsilon_v^p/d\varepsilon_s^p$) increases with temperature. This behavior suggests that the plastic flow rule depends on temperature. Abuel-Naga *et al.* (2007a) also state that the Roscoe surface is steeper with increasing temperature and proposed a thermomechanical model for saturated clays to capture this feature.

MATERIALS

The marine clay used in this study was sampled from the seabed off the coast of Brazil at a depth of 0.70 m from the sea floor under a water depth of 3,000 m. The main physical properties of marine clay are depicted in Table 2. It can be characterized as a very fine material, containing 2.4% fine sand, 27.5% silt and 70.1% clay. The fines fraction exhibits high plasticity with an elevated colloidal activity of 0.93. The clay classifies as CH according to the Unified Soil Classification System (USCS).

The triaxial tests performed as part of this study were conducted on reconstituted clay specimens due to the limited number of intact samples obtained from the field. After removing and homogenizing the clay from the Shelby tubes, it was then reconstituted in a wet chamber to maintain the original gravimetric water content constant with salt water as the porous fluid. The saturation degree at the end of reconstitution was about 95%. Afterwards, the clay was consolidated one-dimensionally inside a cylindrical mold in K_0 conditions using a hydraulic actuator to reach a vertical effective stress of 100 kPa. This process lasted five days and the load was applied in five steps up to desired vertical effective stress. After that, the specimens were then trimmed to an H/D=2 ratio (Height H of 76.2 mm; Diameter D of 38.0 mm) for triaxial testing. After being unloaded during extraction from the cylindrical mold and recompressed isotropically inside the triaxial cell to a minimum effective cell pressure of 100 kPa, the clay specimens were assumed to be normally consolidated as the mean effective stress in the triaxial cell is greater than the mean effective stress in the cylindrical mold under K_0 conditions.

THERMAL TRIAXIAL TEST DEVICE AND METHODS

The experimental program was carried out in a customized thermal triaxial cell manufactured by GDS Instruments. The insulated aluminum chamber allows heating to a maximum temperature of 65 ºC under a maximum cell pressure of 4 MPa. A schematic diagram of the triaxial chamber is shown in Figure 1 with all the instruments installed, including three thermocouples, one displacement transducer, one load cell, one pore pressure transducer, two thermal pads attached to the outside of the aluminum cell, and a back-pressure control system. The sensors incorporated into the thermal triaxial cell were selected to have a stable response within the temperature ranges investigated in this study. Heat is transferred to the test specimen by heating the water inside the cell using computer controlled electrical resistor coils. The volume change and the vertical strain during the heating phase were measured using, respectively, the cell fluid volume and, a servo-controlled device that allowed keeping the vertical load cell always in contact with the top of the soil specimen without delivering any extra load during the heating-cooling process.

The conventional triaxial tests at room temperature, to serve as reference tests for the subsequent tests, were performed following the procedures in ASTM D4767-11(2020) for consolidated isotropic undrained (CIU) triaxial testing. Filter paper strips were used to promote drainage across the specimens. All triaxial tests were performed under back-pressure to ensure that the specimen was saturated (B=0.98 minimum) and involved mechanical consolidation to the target initial effective stress before shearing in constant strain rate of 0.06mm/min. For the thermal triaxial tests, thermal consolidation during heating and uncontrolled natural cooling stages were added after primary mechanical consolidation was achieved, as shown in Figure 2. The characteristics of the thermal additional stages are described in Figure 2, which comprise:

i. Drained thermal consolidation: this additional stage consists of raising the temperature of the specimen up to "T_f" (Fig. 2) under constant hydrostatic stress at a heating rate of 0.5 ºC/min while the drainage valves at the top and bottom of the specimen were kept open to ensure double drainage. The excess of pore pressure during heating was monitored using the pressure sensor attached to the pressure-volume controllers to ensure that it was negligible during drained heating. This stage lasted 24 hours following a common practice adopted during conventional creep oedometer tests on this soil, with the goal of capturing both the primary and secondary thermal consolidation stages in a consistent manner in each test for ease of comparison. Primary thermal consolidation was observed to occur in only a few hours after reaching a stable temperature, while secondary thermal consolidation was not observed to stabilize. Longer periods of heating will undoubtedly lead to additional creep and further decreases in volume, but the goal of this study was to characterize the changes in soil behavior.

ii. Cooling: consists of reducing the temperature from T_f reached in the previous stage to room temperature (T_r) while keeping constant the confining stress. The equipment does not allow a controlled cooling and this phase consisted only of turning off the heater. Accordingly, natural cooling required approximately 12 hours for stabilization of both temperature and volume change at room temperature. The excess pore pressure was not monitored during the cooling phase. However, based on the time required for stabilization it is believed that the cooling phase was also a drained process.

The effect of thermal consolidation on the undrained shear strength of marine clay was experimentally assessed by using two sets of testing. The first set involved reference tests that consisted of standard CIU triaxial tests under confining effective stresses of 100, 200 and 400 kPa at a controlled room temperature of 23±1 ºC. The second set of tests was carried out on specimens with nearly identical initial conditions to those in the conventional room temperature tests (similar initial void ratio and same initial effective confining stress prior to heating), consisted of undrained shearing after 24 hours of thermal consolidation of the specimens under the same confining stresses of the first set. This makes possible direct comparisons between the two sets of tests and, therefore, to quantify possible improvements and substantial differences in mechanical response between them. An additional test, S4, was also carried out in a conventional triaxial test to characterize the Unload-Reload Line (URL) in the compression plane. The experimental testing program involved ten triaxial tests whose details are presented in Table 3. The tests included conventional consolidated-undrained triaxial tests labelled S1 through S3 as well as consolidated-undrained tests after a heating-cooling cycle. These included tests S6, S7 and S8 which were heated up to 40 °C and tests S9, S10 and S11 which were heated up to 55 °C.

RESULTS

Thermal Consolidation

In this section, the results of the thermal consolidation changes of the heated tests are presented, and then the stress-strain response and stress paths from consolidated undrained tests are presented in the next section. It is important to mention that tests S6 to S11 involved heating just after the end of isotropic mechanical primary consolidation. During each stage of consolidation (i.e., mechanical consolidation; drained thermal consolidation and drained cooling), all specimens experienced volumetric strain variation due to changes in void ratio and negligible excess of pore pressure during the second stage. During cooling, the time taken to the chamber to return to the room temperature probably allowed a drained process. The change in void ratio for heating and cooling phases in Figure 3 shows a partial elastic rebound due to cooling. The evolutions in void ratio for the tests at 40 and 55 °C during heating only, normalized by the initial void ratios of each specimen, are plotted against confining stresses in Figure 4. The results indicate that the higher the temperature, the greater the thermal volumetric strains, as expected. After 24 hours of thermal consolidation, the deformations did not show any tendency of stabilization. However, for the specimens heated to 40°C this was even less evident than of specimens heated up to 55°C. On the other hand, the confining stress level does not affect the thermal consolidation process. This reflects a dominant influence of the temperature in the void ratio change, irrespective the initial void ratio achieved at the end of primary mechanical consolidation.

Under constant effective confining stress, thermal consolidation caused a decrease in the void ratio in the specimens. However, this change takes place in two different ways as depicted in Figure 5. During transient heating the specimen experiences some volume decrease of about 0.3 and 1.0% for 40 and 55°C respectively. However, besides the plastic volume change recorded during constant temperature, the volume decrease during the transient phase of heating is fully recovered during cooling and the slope of volume change vs. transient temperature curve is not dependent on effective confining pressure nor temperature. A linear trend fitted to the data indicates that a constant transient thermal volumetric variation coefficient of 0.043 %/°C is encountered during the heating and cooling processes. This slope reflects the tendency of the clay to change in volume under a specific heating rate before the permanent heating compression takes place under stress and temperature constant. It is quite useful for assessing the final void ratio after heating-cooling process. Further studies are needed to investigate the factors influencing this slope (elastic thermal volume change during transient heating).

For both tests, the relative volume change is not dependent on the temperature during thermal consolidation, at least for the temperature ranges tested herein, and both curves show the same pattern keeping a constant difference in volume change from each other. The thermal volume change has greater variation when the confining stress is in the interval of 100 to 200 kPa irrespective of the temperature used during thermal consolidation. From test S6 onwards all further tests followed the same procedures to obtain void ratios e_{f1} (after primary mechanical consolidation), e_{f2} (after heating) and e_{f3} (after cooling) and are presented in Table 4.

Stress Strain Response and Shear Strength Parameters

The deviator stress (σ_d) and excess pore water pressure (Δu) vs. axial strain (ε_1%) curves from all triaxial tests are shown in Figure 6. The results from conventional tests at room temperature allow definition of a peak failure envelope with a slope M=1.07 corresponding to an effective internal peak friction angle (ϕ') of 26.7º; the slopes of the virgin compression and recompression line were λ=0.26 and κ=0.074, respectively. The deviator stress (σ_d) and change in pore water pressure (Δu) plotted as a function of axial strain (ε_1%) from all the thermal triaxial tests in Figure 6 show a considerable increase in undrained shear strength of 88% and 98% for the specimens thermally consolidated at 40ºC and 55ºC, respectively. However, in relation to the pore pressures generated during shear, there were no significant changes.

ANALYSIS

The effective stress paths from these tests are shown in Figure 7 along with the isotropic compression line (LIC), the critical state line (CSL), and the equivalent time compression lines according to the data obtained. The lasts are defined as the lines parallel to the LIC but considering the void ratio after thermal consolidation. At first glance, these results may mistakenly be interpreted that the increase in temperature generated a new failure envelope.

However, the specimens subjected to a heating-cooling cycle have lower void ratios (state parameters) than the unheated specimens. The corresponding void ratios for the thermal triaxial tests after cooling are the e_{f3} whose line in the compression plane is located below the LIC at room temperature as shown in Figures 7(b) and 7(c). For this reason, the effective stress paths of the thermally consolidated specimens showed an increase in mean effective stress (+Δp') at the beginning of shearing closely following the total stress path up to vertical strains of about 1%, which correspond to approximately 60% of mobilized strength, when considerable positive pore water pressures started being generated until the point of failure.

An important feature that the heating-cooling cycle reveals is the strain-rate effects in the shape of the effective stress path for specimens thermally consolidated. Generally, the principle of effective stress does not consider both the viscous and friction effects separately because under the conventional strain-rate adopted in typical laboratory tests they occur simultaneously for fine soils. However, in case of thermally consolidated soils, the viscous contacts tend to disappear, and the solid-solid grain contacts prevail. During the initial stage of shearing, the absence of viscous contacts will require the specimens to undergo additional shear strain before pore-pressure generation occurs. Until there, the effective stress path will coincide with the total stress path and the samples will show higher initial stiffness, as observed herein. This is clearly observed in the zoomed detached area of the Figure 7.

A high gain in undrained strength is achieved when the specimens are thermally consolidated up to 40^{o}C (ΔT = 17^{o}C) when compared with tests on specimens performed at room temperature. For specimens thermally consolidated up to 55^{o}C (ΔT = 32^{o}C) there is a smaller gain in undrained shear strength when compared to those thermally consolidated at 40^{o}C, as shown in Figure 8. Additionally, the overall gain in undrained shear strength becomes more evident with higher confining stresses. This behavior may be associated with the new soil structure achieved after thermal consolidation, as mentioned above, where no pore-pressure is generated up to 1% of vertical strain. This finding is consistent with those reported by Coccia & McCartney (2016). It is well known that the cooling stage shows a significant influence on the thermal hardening process of the clay, as discussed by Coccia & McCartney (2016) where the kinematic viscosity of the adsorbed water plays a major rule, along with the recent stress history of the soil.

On the other hand, the stiffness of the clay specimens is highly impacted by thermal consolidation, which is more evident for those subjected to higher confining stresses once they seem to play major role in the newly formed fabric after heating, as shown in Figure 9. It is known that during undrained shearing in a conventional triaxial test, the viscous strength is instantaneously and fully mobilized as it depends on the strain rate only. Due to its lower compressibility, the free water is loaded first and the pore water pressure is generated at low levels of deformation. This mechanism is closely related to the presence of bonded water films covering the soil particles as stated by Taylor (1942). Thermal consolidation seems to cause more effective grain to grain contacts, as explained before. For specimens consolidated at 400 kPa and subjected to thermal consolidation under temperatures up to 55 ^{o}C ($\Delta T=32^{o}C$) the stiffness can reach values of five times the stiffness at room temperature. Moreover, this considerable change in stiffness also takes place for the other specimens consolidated under lower confining stress, however with less intensity. This culminates in less pore water pressure being generated at the beginning of the shearing process.

According to the results from the triaxial tests, the void ratio for clay specimens at the end of thermal consolidation is somewhat smaller than that of clay specimens consolidated to the same conditions at room temperature as shown in Figures 7(b) and 7(c). However, during the cooling phase this difference may decrease, but this is not reflected in the strength properties. This situation could also be represented within the critical state framework using the concept of equivalent initial pressure.

Considering that the undrained shear strength, s_u, can be defined by:

$$s_u = \frac{M}{2} \cdot \frac{p'_i}{2^{\Lambda}} \tag{1}$$

where M is the slope of the peak failure envelope and $\Lambda = \frac{\lambda - k}{\lambda}$. Once s_u is obtained from the triaxial tests on a heated specimen, it is possible to use Eq.1 to define the equivalent initial effective isotropic confining stress, p'_{ieq}. This approach was followed using the undrained shear strengths for each test and the equivalent initial effective isotropic confining stresses are summarized in Table 5. Therefore, a value of p'_{ct} can be defined as the isotropic pressure where the value of void ratio on the isotropic compression line coincides with the void ratio reached at the end of thermal consolidation under a given consolidation pressure. This procedure defines a so-called pseudo/equivalent consolidation stress "p'_{ct}" caused by heating only, as depicted in Figure 10, as similarly proposed by Abuel-Naga *et al.* (2007b). As the result, the undrained strength defined by the shifted effective stress path will match the critical state line, which in turn is not affected by the heating, as shown in Figure 11. Consequently, by using the same value of undrained strength for the shifted effective stress path for each test and using the Cam-Clay relationship in Equation (1) to assess the equivalent initial confining effective stress, p'_{ieq} as listed in Table 5, comparison between both effective stress-paths can be done. The Figure 12 shows that the effective stress paths predicted from the Cam-Clay model is somewhat different in shape from those obtained from the thermal triaxial tests, although the undrained strengths are the same. This indicates that the decrease in void ratio, due to the increase in temperature, is not the only reason for the observed increase in undrained shear strength and the resulting soil structure plays an important role in the undrained mechanical response of thermally consolidated soils.

CONCLUSIONS

This study presented a detailed evaluation of the thermal improvement process of soft, high plasticity clays that may be gained during a drained heating-cooling cycle under different effective confining stresses. A clear decrease in void ratio was noted after the heating-cooling cycle due to a combination of primary and secondary thermal consolidation, with greater changes for higher changes in temperature and higher initial effective confining stresses. The results suggest that the thermally consolidated clay specimens behave as very stiff body until 1% of vertical strain is reached and after which an increase in pore pressure occurs. The definitions of the normally consolidated line and isotropic thermal consolidation lines were necessary to numerically define the equivalent consolidation stress p'_{ct} values and to adjust the effective stress path for the thermally consolidated sample, which fits well in the critical state line that, in turn, is not affected by the temperature change. However, the shape of the effective stress path followed by the thermally consolidated specimens is quite different from those defined by the Cam-Clay model, as this model does not consider strain-rate effects which seems to be critical in thermally consolidated fine soils.

Application of a heating-cooling cycle to the clay specimens with maximum temperatures of 40 and 55 °C was found to result in 88% and 98% increases in undrained shear strength, respectively, when compared to the same tests consolidated at room temperature. No significant difference in the rate of volume change for both temperatures tested was found and this reflects in the low difference among the undrained strength for specimens consolidated under 40 and 55 °C. This is believed to result from the fact that the water viscosity does not change significantly for temperatures greater than 40 °C above which the rate in water viscosity variation falls from 0.02 to 0.005 mPa.s/°C. At the same time, the major change in soil structure takes place up to 40 °C.

This study provides unique insight into the thermo-mechanical response of high plasticity soft clays that can experience significant thermal creep after the end of primary thermal consolidation. From a practical perspective, the results of this study may have promising implication in using thermal consolidation of soft clays to improve the pullout capacity of deep water anchors like torpedo piles embedded in the clay, with the heating element installed within the pile. The water temperature off the coast of Brazil, in deep water, is somewhat constant around 4 °C and small changes in temperature will make water viscosity vary considerably which may help promote the clay thermal consolidation process.

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TABLE 1. Summary of conclusions regarding the influence of temperature on shear strength.

Reference	Soil type	Condition	Type of heating	Type of shear	Remarks
Houston *et al*. (1985)	Ocean sediments (illites and smectites).	NC	U	CIU	Undrained shear strength increased when drained thermal consolidation took place at high temperatures.
Hueckel & Baldi (1990)	Boom clays and one clay slime.	OC	D	CID	Shear strength declined in both cases.
Lingnau *et al.* (1996)	Mixture of silica sand and sodium bentonite.	NC	D	CIU, CID	Strength is independent of temperature.
De Bruyn & Thimus (1996)	Boom Clay	NC	D	CIU	Decrease in strength due to the decline in friction angle and a slight rise in apparent cohesion.
Kuntiwattanakul *et al.* (1995)	Kaolin clay	NC, OC	D	CIU	Increase strength in NC but it is not observed for OC soils
Graham *et al.* (2001)	Reconstituted illite	OC	D, U	CID	The critical state line is independent of temperature.
Burghignoli *et al.* (2000)	Reconstituted and natural clay	NC	D, U	CIU	Strength is independent of temperature.
Cekerevac *et al.* (2005)	Kaolin	OC	D	CID	Shear strength increased only for NC conditions.
Abuel-Naga *et al.* (2007a)	Soft clay (LL=103%)	NC, OC	D	CID and CIU	Shear strength increased for both cases, NC and OC.
Uchaipichat & Khalili (2009)	Silt	NC, OC	U	Suction Controlled CD	Peak shear strength decreased but at critical state condition there was no temperature effect
Shibasaki *et al.* (2017)	Smectite	NC	D	CD - Direct shear	Shear strength increased.
Samarakoon *et al.* (2018)	Kaolinite	NC	U	CIU	Higher strength after thermal consolidation with even higher strength after subsequent cooling before shearing.

D = Drained, U=Undrained, OC=Overconsolidated, NC=Normally Consolidated

TABLE 2. Physical properties of natural marine clay.

Parameter	*Value*
gravimetric water content (w) "after homogenization (%)"	91.2
Liquid limit (LL)	106
Plastic limit (PL)	41
Plasticity index (PI)	65
Specific gravity (G_s)	2.69

TABLE 3. Total number of tests and their respective characteristics.

Test	*Effective confining stress (kPa)*	*OCR*	*Thermal consolidation temperature (ºC)*	*Shearing temperature (ºC)*
S1	100	1	23 (none)	23
S2	200	1		
S3	400	1		
S4	50	4		
S6	100	1	40	23
S7	200	1		
S8	400	1		
S9	100	1	55	
S10	200	1		
S11	400	1		

TABLE 4. Initial and final physical properties of the specimens.

Test	w_i (%)	e_o	w_f (%)	e_{f1}	e_{f2}	e_{f3}
S1	70.63	1.90	55.02	1.48	-	-
S2	73.23	1.97	50.19	1.35	-	-
S3	71.00	1.91	41.26	1.11	-	-
S6	70.63	1.90	54.65	1.48	1.45	1.47
S7	73.23	1.97	49.81	1.36	1.32	1.34
S8	73.61	1.98	40.89	1.14	1.09	1.10
S9	71.38	1.92	53.90	1.50	1.42	1.45
S10	69.89	1.88	46.10	1.29	1.20	1.24
S11	70.26	1.89	39.03	1.09	1.01	1.05

$w_{i,}$ = initial gravimetric water content
w_f= final gravimetric water content (after cooling when applied)
e_o = initial void ratio

TABLE 5. Equivalent effective mean initial stress $p'_{i\,eq}$ by using the Cam-Clay approach.

p'_i	55°C	40°C	Cam Clay	23°C	40°C	55°C	$p'_{i\,eq}$	
kPa	e_{f3}		s_u (Eq 1)	s_u-triaxial			40°C	55°C
100	1.45	1.48	32.0	35.0	82.0	90	255.90	280.86
200	1.29	1.36	64.0	67.0	150.0	165	468.10	514.91
400	1.09	1.14	128.2	158.0	285.0	300	889.39	936.20

$p'_{i\,eq}$= Initial confining effective stress necessary to provide the same s_u obtained by triaxial tests. Strength and stress in kPa.

Figure 1. Schematic of the thermal triaxial cell.

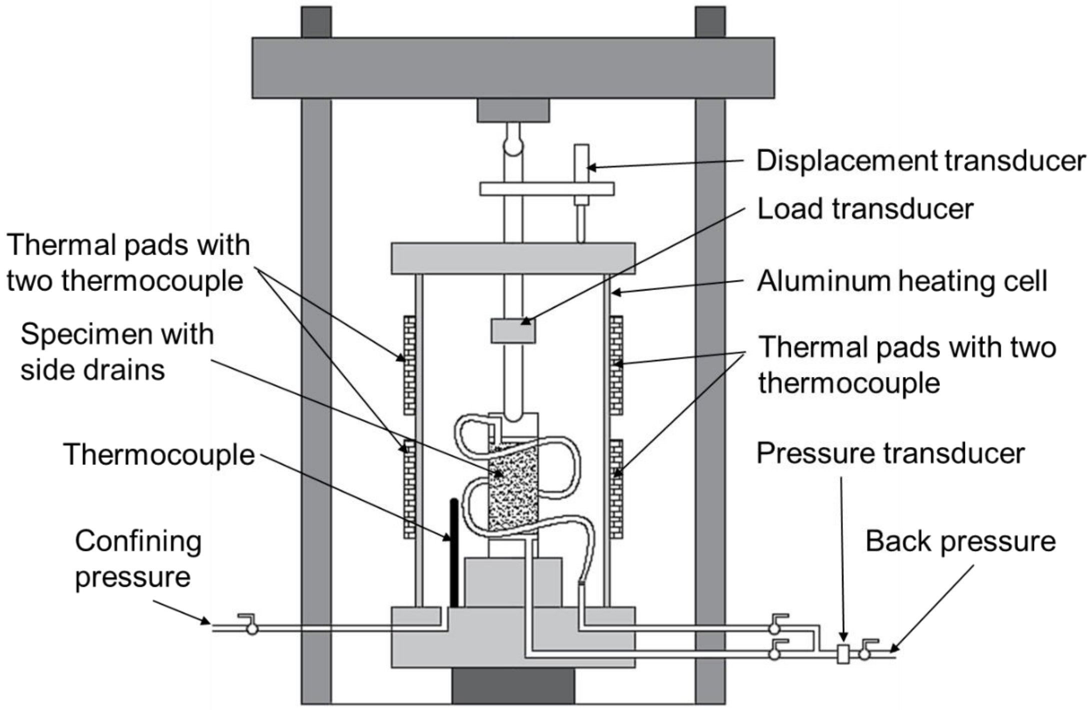


Figure 2. Procedure used for CIU thermal triaxial tests.

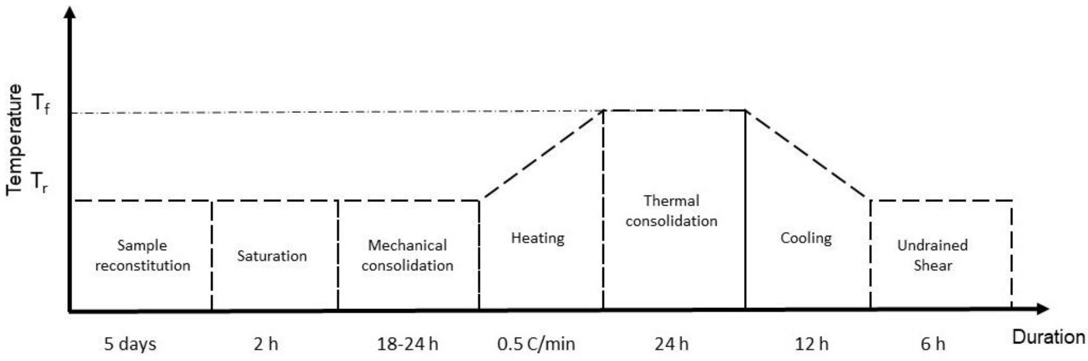


Figure 3. Void ratio variation during thermal consolidation for S6, S7 and S8 tests

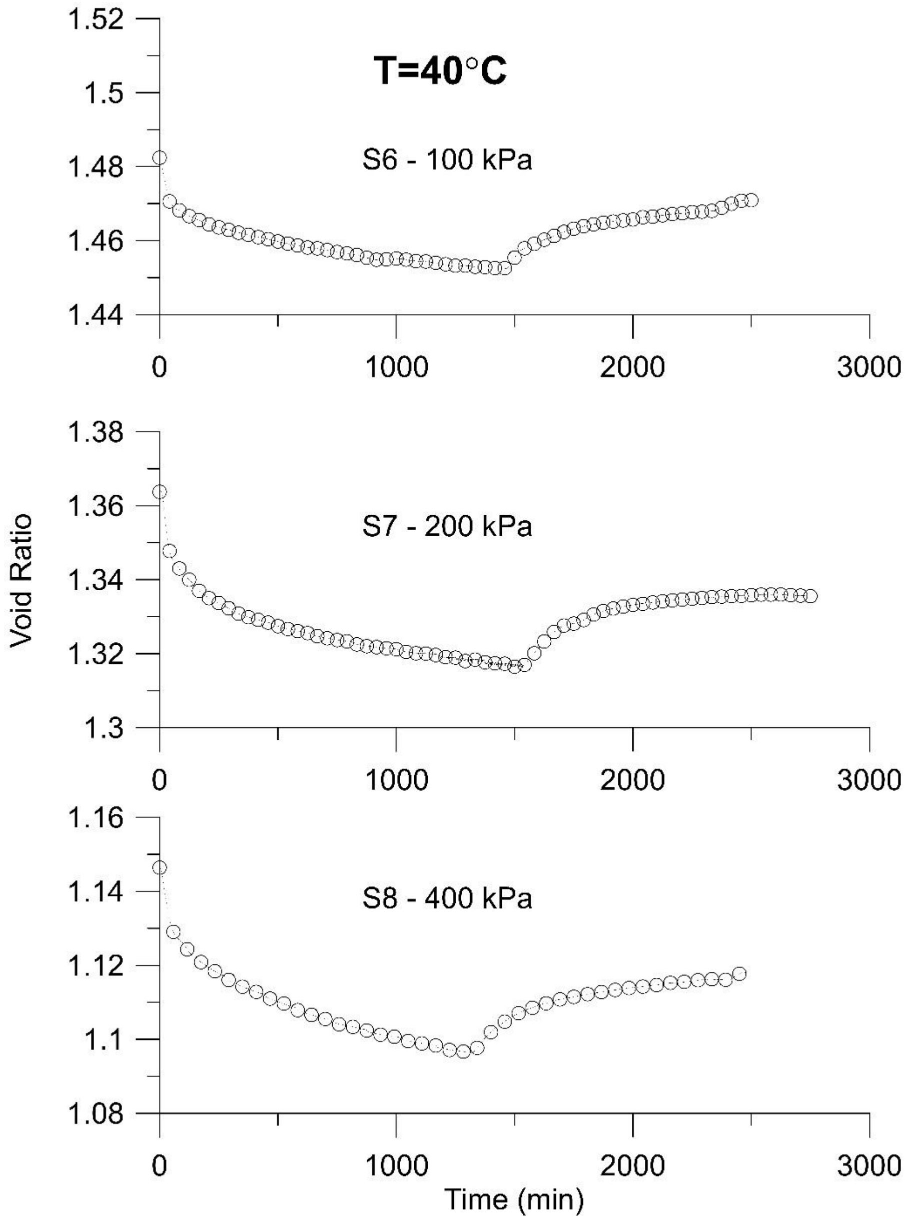


Figure 4. Transient evolution in volumetric thermal strains after heating to 40ºC and 55ºC.

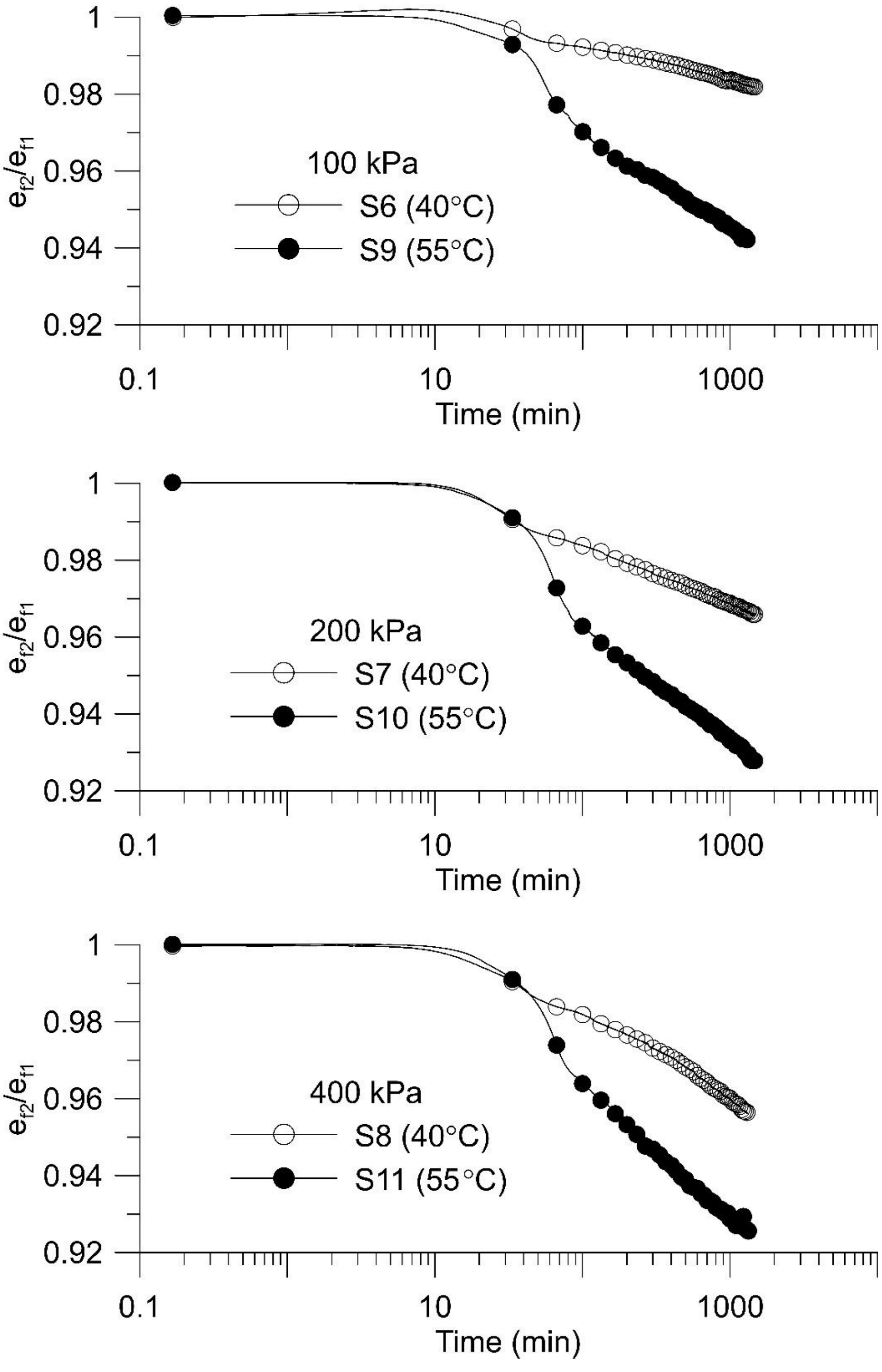


Figure 5. (a) Thermal volumetric deformation (Ɛv) vs. temperature (T) curves of the thermal triaxial tests at 40ºC and 55ºC. (b) Thermal volume change under constant temperature and confining stress.

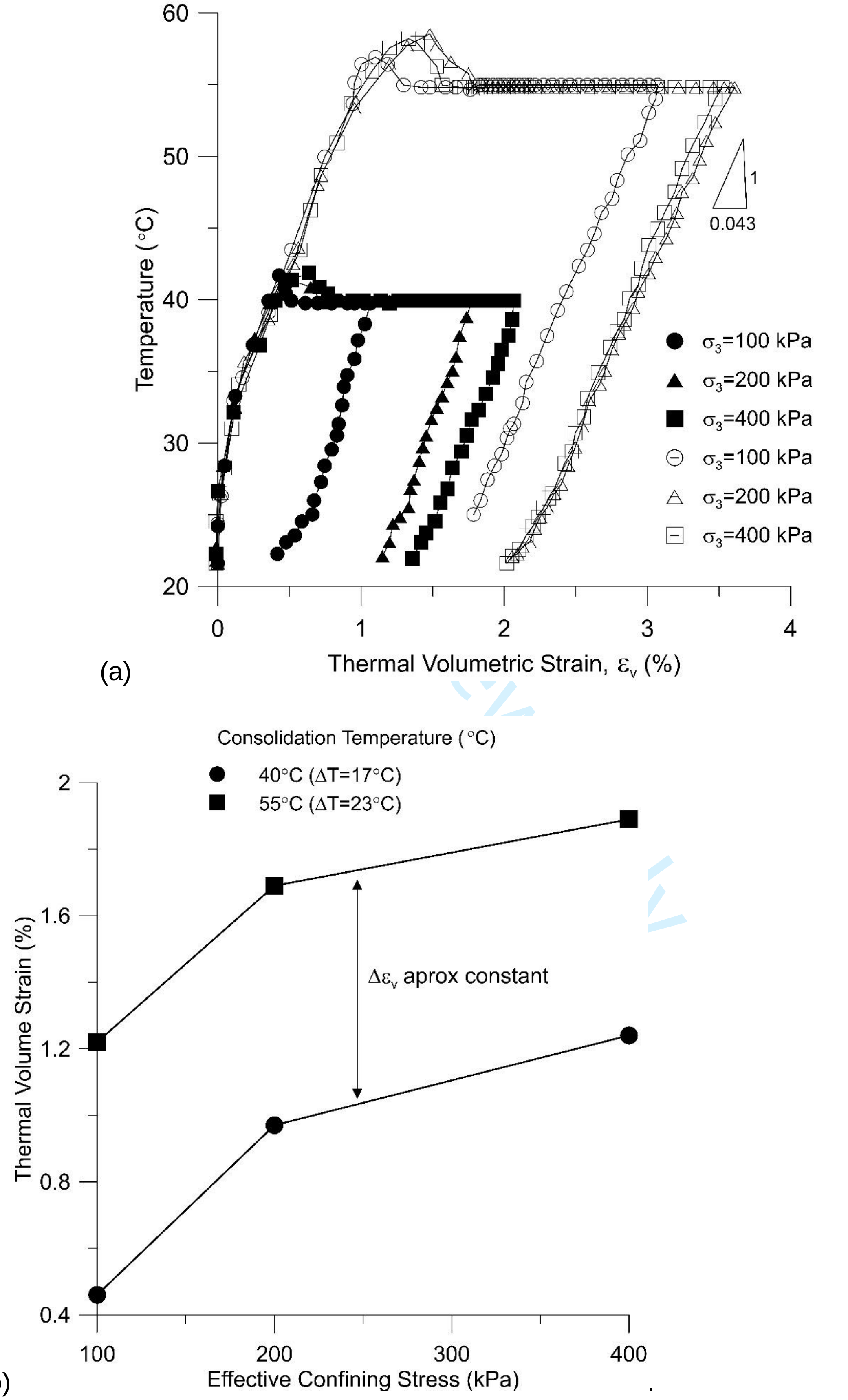


Figure 6. Deviator stress vs. axial strain (σ_d vs. ε_1); (a) and pore pressure vs. axial strain (Δu vs. $\varepsilon 1$) Tests S1 to S3 (references); (b) S6 to S8 (thermal consolidated at 40°C); (c) S9 to S11 (thermal consolidated at 55°C).

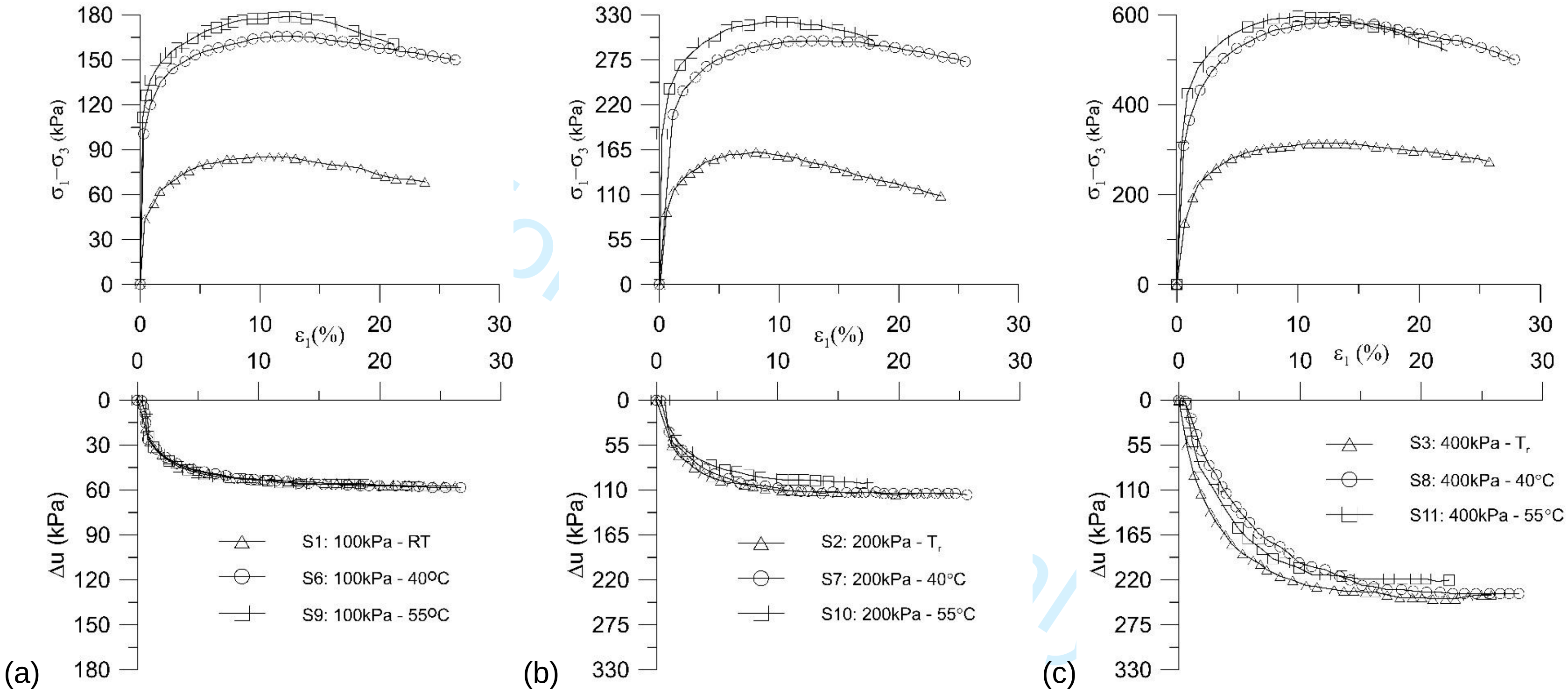


Figure 7. (a) Effective stress paths (ESP), (b) LIC and CSL in the compression plane and (c) equivalent time compression line in ln p´ vs. vol. strain in the compression plane for conventional and thermal triaxial tests

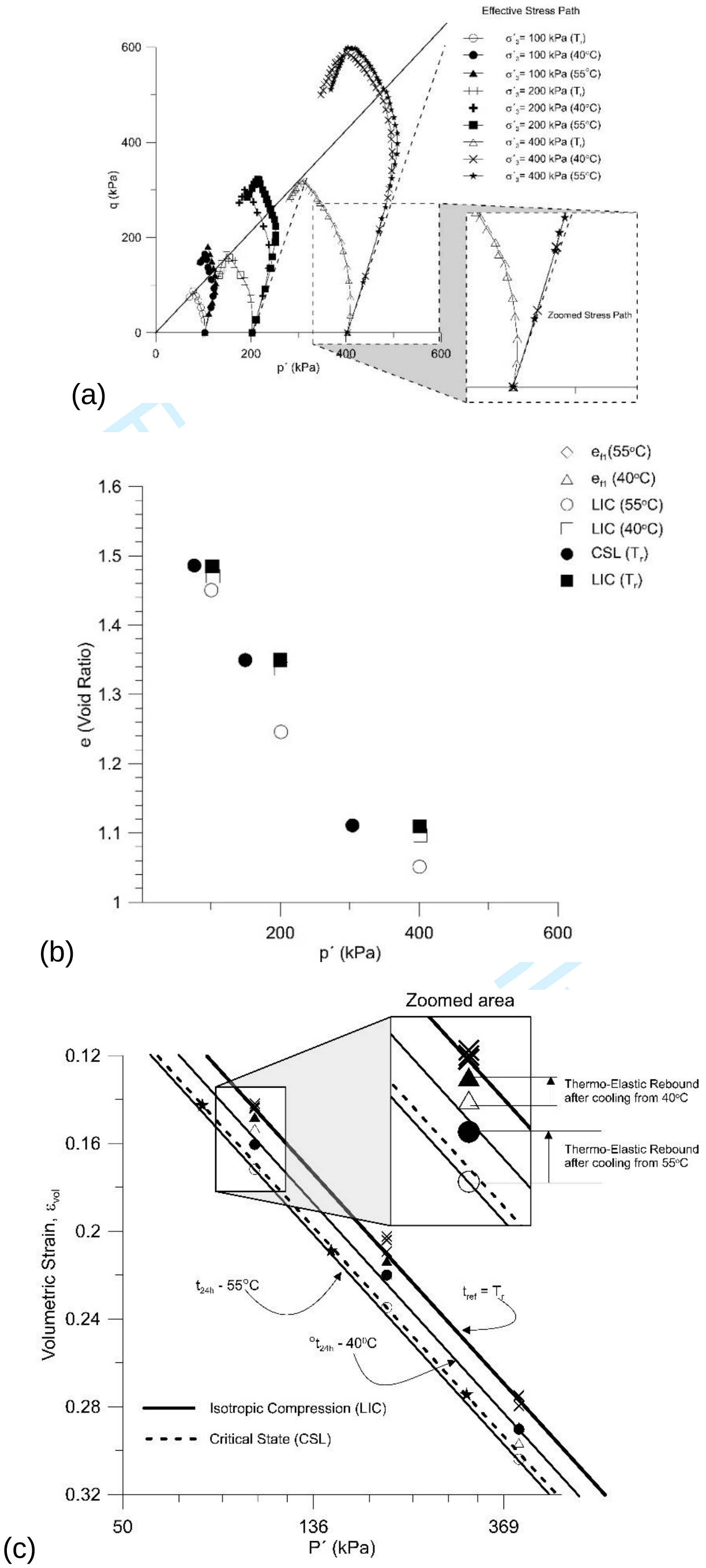


Figure 8. Changes in undrained peak shear strength with thermal consolidation.

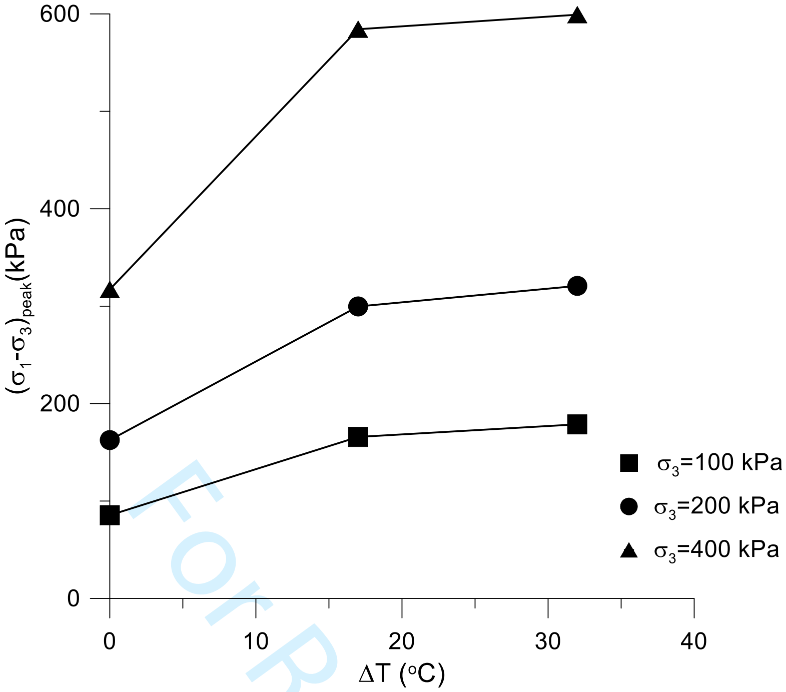


Figure 9. Young's modulus defined at 1% axial strain for tests at different confining stresses and temperatures.

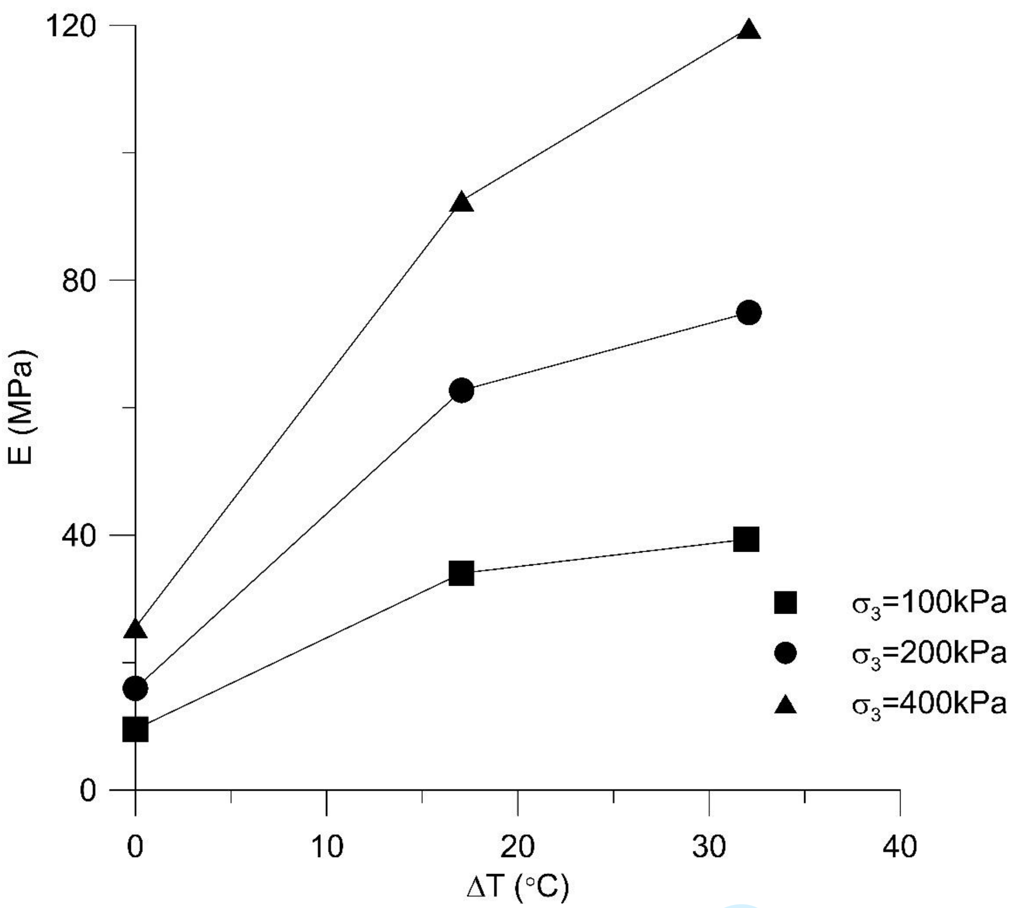


Figure 10. Equivalent or pseudo consolidation effective stress (p'_{ct}) generated by thermal cycle up to 55°C.

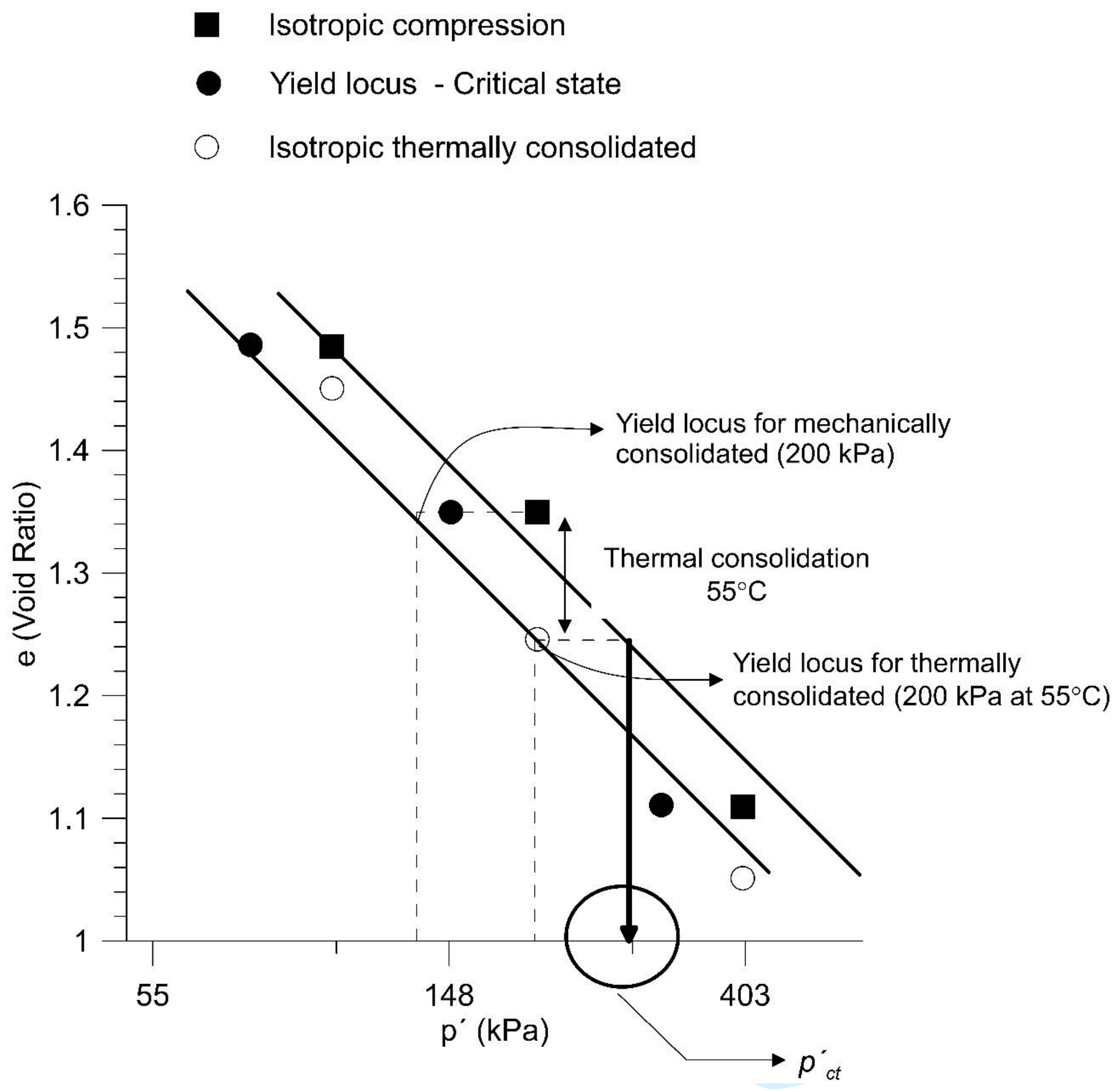


Figure 11. Effective stress paths for thermal triaxial tests at 55ºC with the thermal equivalent pre-consolidation effective stress "p'_{ct}".

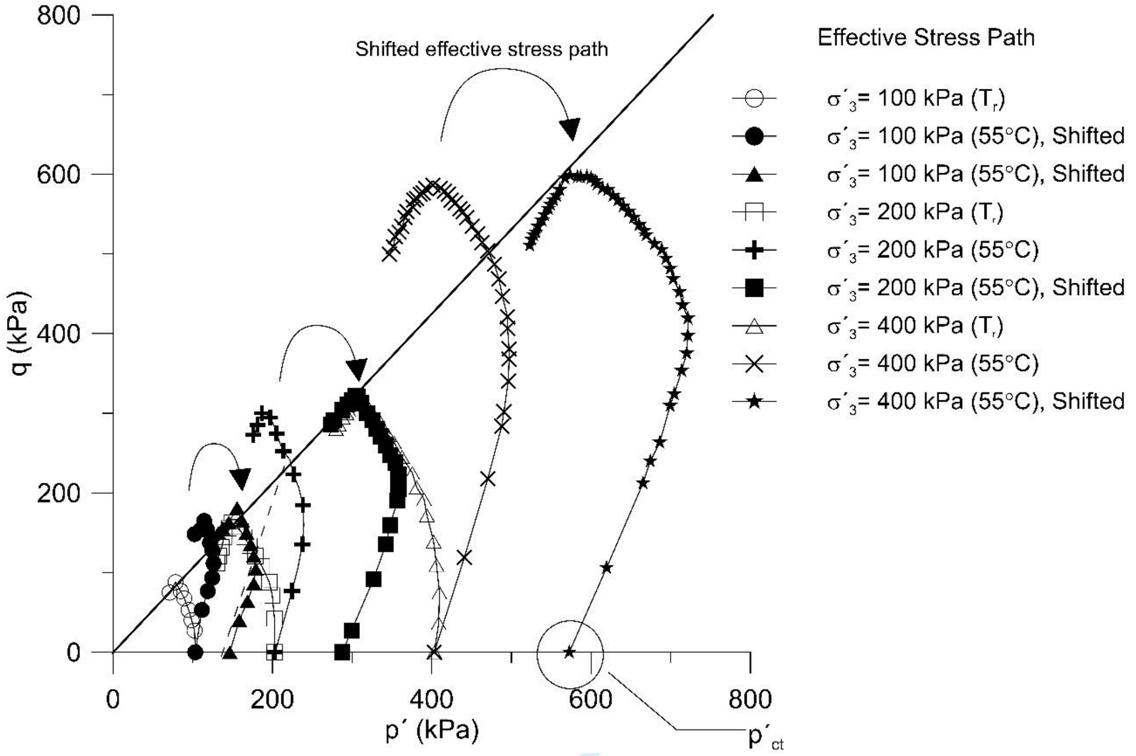
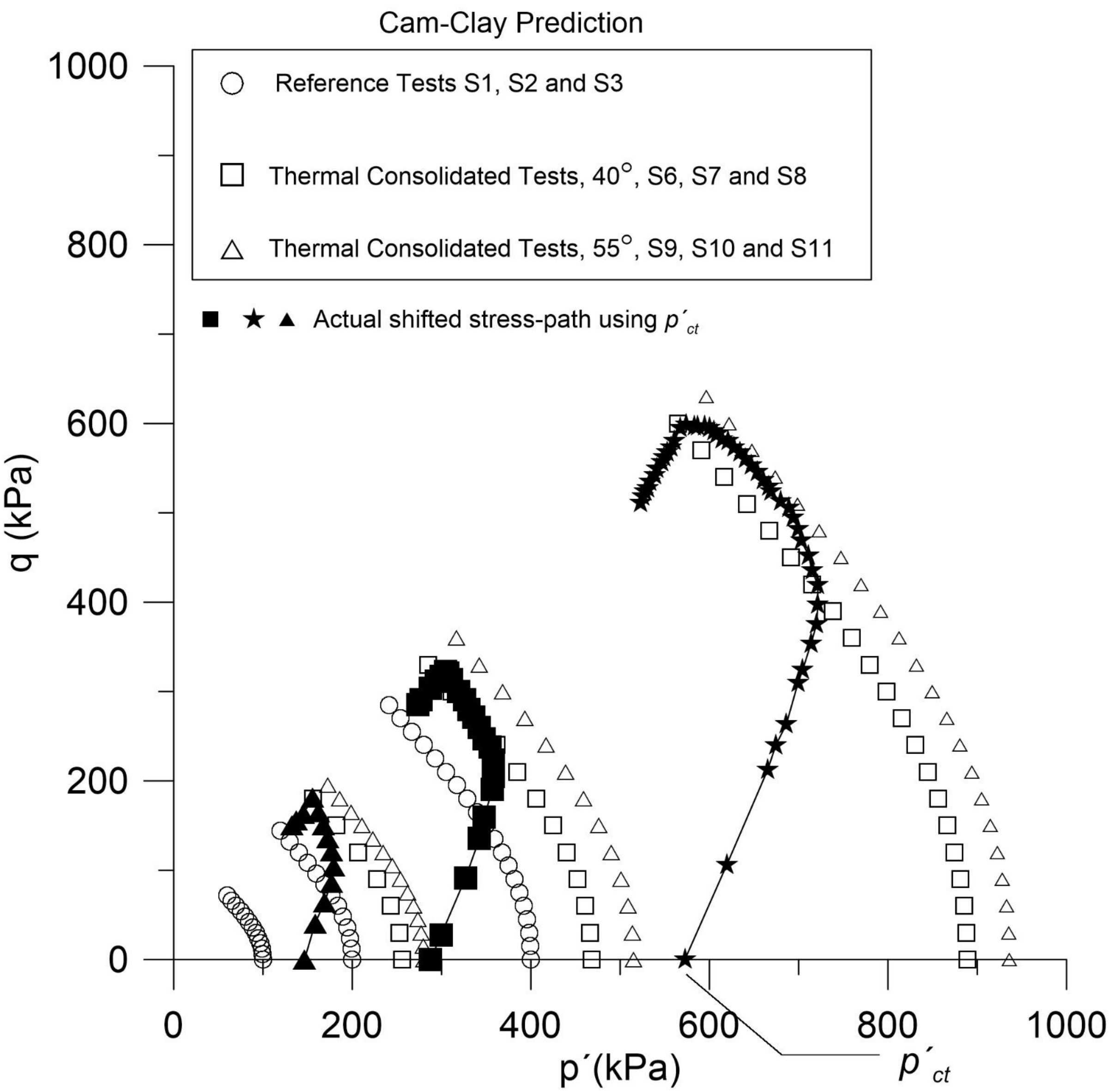


Figure 12. Cam-Clay effective stress path and observed shifted effective stress path



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