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Session 4 Report: Issues Involved with Thermo-Active Geotechnical Systems: Characterization of Thermo-Mechanical Soil Behavior and Soil Structure Interface Behavior

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Abstract

This paper focuses on the main issues discussed during a session on the impact of thermo-hydro-mechanical behavior of soils on thermo-active geotechnical systems, and how they could affect the performance of thermo-active geotechnical systems. Both soil behavior as well as soil-structure interaction behavior were discussed. The main observation from the session was that the thermo-hydro-mechanical behavior of saturated soils has reached a mature understanding, with several established constitutive models that can be used by engineers. However, there are still opportunities to enhance these constitutive models by considering issues such as unsaturated conditions, anisotropic stress states, cyclic heating and cooling effects, and changes in the preconsolidation stress during heating and cooling. Further there are still opportunities to improve our understanding of soil-concrete interface behavior, including the development of novel testing approaches.

KEY WORDS: Thermo-active, soil behavior, geotechnical structures, thermal, thermo-mechanical

1. Introduction

Within the context of the International Workshop on Thermoactive Geotechnical Systems for Near-Surface Geothermal Energy held at the École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland in March 2013, a breakout session was organized around the topic of "issues involved with thermo-active geotechnical systems". The session focused on a variety of behavioral questions regarding thermo-active geotechnical systems, including the effects of temperature on soil behavior as well as the interfaces between soil and other thermo-elastic materials such as concrete or steel. The response of thermo-active geotechnical systems to cyclic thermal loading and the possibility of thermal fatigue are also subjects that are not well understood that were discussed in the session.

The main objectives identified for the session were to identify and categorize specific issues related to thermo-mechanical soil behavior and performance of thermo-active foundations that are well understood in the literature, then to identify the pressing challenges in the thermo-hydro-mechanical (THM) characterization of soils for thermo-active foundation systems. These issues were established by transferring lessons learned from research on other energy geostructure applications (i.e. nuclear waste storage) in terms of THM soil behavior. This paper provides a review of the different topics discussed in the session along these lines.

2. Thermo-Mechanical Behavior of Soils

2.1. Thermo-Mechanical Laboratory Testing of Soils

Some of the thermo-mechanical (TM) questions regarding the behavior of soils are being answered through laboratory testing using thermo-mechanical triaxial cells, thermo-mechanical isotropic cells and oedometers with temperature control. Laboratory TM testing of soil is a new frontier, and there are many issues to address such as developing sufficient heating systems, isolation and accounting for thermal losses, thermal calibration, control of boundary conditions, and representing long-term cyclic behavior. In terms of heating systems, modifications are done on conventional laboratory equipment in order to apply thermal loading on the soil specimen. There are several methods used for thermal loading, the main difference between these methods being the way the heating and cooling is applied on the sample. A list of different methods utilized for thermal loading of soil samples are shown in Table 1. The methods can be categorized in three main groups: heating by circulating fluid, heating with internal heaters, and heating with external heaters (Cekerevac et al., 2005).

The independence of the heating system, the uniformity of the temperature, the time required to bring the sample to the desired temperature, the insulation of the heating system and the accuracy of the temperature monitoring are main requirements in thermo-mechanical laboratory testing of soils. Another issue related to the thermo-mechanical laboratory testing of soils is the isolation and accounting for thermal losses. In order to minimize the temperature difference between the applied and obtained temperatures and decrease the heat transfer to the exterior, insulators are being used around the thermo-mechanical testing equipment. Another important factor in maintaining a constant temperature is to perform the tests in a temperature-controlled laboratory environment. High accuracy temperature sensors placed in/around the samples allows the monitoring of thermal losses, which is very important to be taken into consideration.

A third issue in thermo-mechanical laboratory soil testing is the thermal calibration. Temperature changes induce volume variation of the sample as well as the volume change that occurs due to thermal dilatation of the testing apparatus. It is very crucial to separate the testing apparatus' response from the sample's response. Although a large number of studies did not report thermal calibration, a thermal calibration approach is well documented by Abuel-Naga et al. (2006) and Cekerevac et al. (2005) for oedometer and triaxial apparatus, respectively. Abuel-Naga et al. (2006) assessed the thermal deformation of the oedometer apparatus due to the non-isothermal test conditions in terms of thermal vertical dilatation of the oedometer apparatus and thermal diametrical strain of the oedometer ring. The thermal vertical dilatation of the oedometer apparatus was measured at different stress levels and used to correct the measured readings under non-isothermal conditions during actual tests. The diametrical strain of the oedometer ring was measured at different temperature levels. The constant volume assumption was then used to express the thermal diametrical expansion in an equivalent vertical deformation. Taking into consideration the effect of soil particle dilation, the calculated error in the void ratio due to the thermal diametrical strain of the oedometer ring was found to be insignificant.

In Cekerevac et al. (2005) approach the volume change of the triaxial system is characterized at different temperatures and confining pressures by using a metallic sample with a known value of volumetric thermal dilation. In the same study, the deformation of the pedestal is ignored due to the fact that the samples were heated before being sheared, thus any deformation would have taken place before testing. Delage et al. (2000) used relationships from Campanella and Mitchell (1968) and Baldi et al. (1988) to account for the volume of water that was expelled during drained tests. Another issue related to thermal calibration is the control of boundary conditions. For example, contraction during heating may result in loss of contact thus rendering automated testing more challenging. As with traditional soil mechanics with regards to the consideration of long-term cyclic effects, the long-term cyclic effects of temperature loading in the laboratory is a further issue that must be addressed. There are both daily (small magnitude, high frequency) and seasonal (large magnitude and low frequency) temperature cycles to consider.

2.2. Future of Thermo-Mechanical Laboratory Testing of Soils

In looking the future of laboratory TM testing of soils, several items must be considered ranging from its role in traditional soil mechanics to the developing of testing methods and equipment specifically for engineering applications to standardization of tests. The thermo-mechanical aspects of soil behavior have not been included in traditional soil mechanics courses taught to undergraduate and graduate students. Due to the significant role, TM aspects of soil behavior are likely to play in the future, perhaps the inclusion of it should be considered. Several schools in the United States, most notably Virginia Tech, University of Wisconsin and the University of Colorado Boulder, are beginning to implement this material. Additionally, very few soil testing laboratories are capable of handling temperature related issues. Most, if not all, of the laboratories with this capability are at academic institutions so there is an opportunity for expansion. One possible path forward in this approach is to develop new testing standards through ASTM.

Expansion from academia to industry may be facilitated through the development of testing methods and equipment that are designed for engineering purposes. In-situ testing devices comparable to the pressure-meter or the cone penetrometer could be modified or developed for thermo-mechanical applications. Additionally the question must be asked at what point the standardization of thermo-mechanical tests takes place. Currently, this appears to be a long way off as the number of places around the world who are capable of running these tests is few and the results from each test depend heavily on the way the test is run.

2.3. What is Already Known about the Thermo-Mechanical Behavior of Soils?

It is known and has been shown that normally consolidated clays contract and highly overconsolidated clays dilate when heated and volumetric change depends on the loading history of soils. Also, as a result of temperature changes in drained conditions, normally consolidated clays show an irreversible volume change whereas highly overconsolidated clays show reversible behavior (Laloui and Cekerevac, 2008; Abuel-Naga et al., 2007; Cekerevac et al., 2005; Graham et al., 2001; Hueckel et al., 1990; Baldi et al., 1988). This behavior can be seen in Figure 1, which shows the drained heating-cooling test results of saturated Kaolin clay at different over consolidation ratios (Laloui and Cekerevac, 2008). During drained heating of normally consolidated samples, the heating results in thermal hardening and hence densification, even if there isn't any changes in effective stresses. However, highly overconsolidated samples show mostly reversible dilation. The magnitude of reversible and irreversible parts of the volume change is explained by the authors as depending on the soil type, soil plasticity and the loading history of soils.

In the study of Abuel-Naga et al. (2007a), the thermally induced volumetric strain is separated into two components: reversible expansion and irreversible contraction. The irreversible contraction component of strain is explained by the particle rearrangement. On the other hand, the reversible expansion component of strain is decomposed into two sub-components. The first one is, the expansion of clay minerals and pore water. The second one is the increase in repulsive forces between clay particles that are subjected to heating which is compensated by an increase in inter-particle spacing. For normally consolidated clays the irreversible contraction component, for highly overconsolidated clays, the reversible expansion component dominates, respectively.

The volumetric strain data for Kaolin clay specimens having different overconsolidation ratios (OCR) during drained heating are plotted in Figure 2 (Cekeravac and Laloui, 2004). As mentioned before, the normally consolidated clay shows contraction during heating, which will likely be followed by further contraction during cooling. Lightly overconsolidated clay (OCR<2) shows a smaller contraction compared to normally consolidated clays with a transitional behavior to expansion as the OCR increases. Highly overconsolidated clay (OCR = 12) shows expansion, although after a certain temperature the soil is observed to contract. It is possible that there is a thermal threshold at which contraction will start to occur, but further research is needed to confirm this for different soils and a wider range of OCR values.

The volumetric strains for various clays, with different overconsolidation ratios, subjected to a temperature increase of 20-40°C are shown in Figure 3(a). For comparison, the volumetric strains of the same clays subjected to a temperature increase of 60-80°C are shown in Figure 3(b). It can be observed from the figures that there is a transition between contraction and dilation with respect to OCR similar to the results presented earlier. The temperature at which transition from contractive to expansive behavior occurs depends on both the OCR and the soil type. The thermally induced volumetric strain of saturated clays depends also on the activity of the specimen. Skempton (1953) considered that the volume change potential of a clay soil is a function of plasticity index and clay percentage; where higher activity corresponds to a higher volume change potential. The results shown in Figure 4 confirm that the thermal volumetric strain increases with increasing activity and increasing temperature.

2.4. New Opportunities for Understanding the Thermo-Mechanical Behavior of Soils

2.4.1. Effects of Soil Anisotropy on Thermally Induced Volume Change of Soils

There has not been a significant amount of research into the role of anisotropy on the thermal volume change of soils. The soils surrounding thermo-active piles will likely be in an anisotropic stress state where the vertical stress is greater than the horizontal stress. Coccia and McCartney (2012) used a thermo-hydro-mechanical true triaxial cell to evaluate the role of stress-induced anisotropy in the thermal volume change. They applied a change in temperature to the top and bottom of a soil specimen using rigid platens in the intermediate stress direction, and measured the thermal volume changes in the major and minor principal stress directions. The ratio between the major and minor principal stresses decreased slightly, as shown in Figure 5. However, the specimen tended to expand in the direction of the minor principal stress (higher OCR) and contract in the direction of the major principal stress (OCR closer to 1.0). The stress in the intermediate direction was not monitored; therefore further research is necessary to fully understand the role of anisotropy and restraint provided to the soil during heating.

2.4.2. Effect of Temperature Cycles on Thermo-Mechanical Behavior of Soils

Another issue that requires further research is the effect of temperature cycles on the thermo-mechanical behavior of soils and soil-pile interface. The initial heating process is expected to lead to an expansion of the thermal yield surface, which implies that subsequent cooling and heating cycles below the previously applied temperature should lead only to elastic, expansive thermal volume changes. However, cyclic effects have been observed by Campanella and Mitchell (1968), Burghignoli et al. (1992), and Vega and McCartney (2014), where small continued thermally induced changes in volume were observed after the first heating-cooling cycle, as observed in Figure 6. These small changes may have a long-term impact on thermally active geotechnical systems. Stewart and McCartney (2014) observed that four temperature cycles had a small effect on the soil-structure interaction on an end-bearing thermo-active pile in unsaturated silt. Cyclic effects may play a more important role in semi-floating energy foundations. The shake down effect, which occurs when a certain number of cycles are required for deformations to stop, occurs in metals and may occur in thermo-active piles as well. If so, it is important to evaluate how many cycles it takes to reach steady-state, which may be on a very long term scale as there are two major temperature reversals per year in most thermo-active piles, but many smaller reversals on a daily basis. The cycle that mainly affects the soil is the seasonal one, which is directly related to the life of the building. The highest temperature change occurs right at the circulation pipes and propagates towards the soil around the pile. Another question arises at this point on what is the temperature variation at the soil-pile interface. All in all, in respect to ultimate bearing capacity, the stresses induced by temperature variations can be possibly neglected however, this needs to be validated and the maximum allowable temperature swing should be included in the standards.

2.4.3. Effect of Temperature Changes on Shear Strength of Soils

There are still pending questions on the effect of temperature changes on the shear strength of the soil. Although there are a significant number of studies performed on this issue, it still remains to be a subject of controversy. There are studies that report that temperature increase strengthens clay. On the other hand, there are many experimental results showing that an increase in temperature can slightly reduce the shear strength. Distinct variations in behavior due to soil type, mineralogy, overconsolidation ratio, drainage conditions during heating and shearing are considered some of the variety of factors causing this discrepancy. In addition, Hueckel et al. (2009) declares that insufficient emphasis on the thermal and mechanical history of the soil specimen is one of the main reasons of the confusion. As a result it is not possible to obtain a clear trend on the effect of temperature changes on shear strength. Table 2 summarizes the heating and shearing methods and the results reported in these studies.

Most of the studies report that heating causes a strengthening in clay when heating is applied under drained conditions. In this method, as the temperature of the specimen is increased, the pore water is drained out and the void ratio of the specimen decreases, which means a stiffer specimen is obtained. Then at this high temperature, specimens are sheared undrained. In the study of Abuel-Naga et al. (2007c), soft Bangkok clay is heated under drained conditions and then sheared undrained. It is reported that the undrained shear strength of soft Bangkok clay increases with increasing temperature regardless of whether the specimens are normally consolidated or overconsolidated. Kuntiwattanakul et al. (1995) performed the same procedure to Kaolin clay specimens and also reported that strength increases with increasing temperature. On the other hand, Kaolin clay specimens that were heated to a certain temperature and then cooled back to room temperature did not show a significant change in strength. The test results from Todi clay (Burghignoli et al., 2000) specimens show that the undrained shear strength increases slightly, but the authors report that shear strength is not appreciably affected by the temperature change of 30°C.

In the study by Cekerevac et al. (2005), Kaolin samples were heated and sheared under drained conditions. It is reported that the samples sheared at higher temperature have a higher strength and brittle behavior. The effect of temperature is more pronounced for normally consolidated clays than for overconsolidated clays. In the same study, the strength of the heated samples and the strength of the samples at room temperature have similar values at large strains. The respective values of soil strength from various studies plotted versus temperature change are shown in Figure 7.

The studies which report a decrease in clay strength upon an increase in temperature are separated in two groups: the tests that use drained heating and the tests that use undrained heating. Campanella and Mitchell (1968) performed drained heating and undrained shearing on Illite clay. The decrease in strength is explained by the increase in thermal energy, which in turn increases the probability of bond slippage. In the study of Hueckel and Baldi (1990), specimens of Pontida silty clay are subjected to drained heating and drained shearing. It is reported that the yielding and the failure at high temperature occurs at a lower deviatoric stress because of the shrinkage of the yield surface. Regardless of these explanations, the results speak for themselves as they show some decrease in shear strength upon heating. It is also indicated that temperature increase reduces the brittleness of the Pondita silty clay which is opposite of the observations reported in Cekerevac et al. (2005). The test results of Moritz (1995) also show that an undrained increase in temperature causes a decrease in undrained shear strength of Swedish clay samples and a more ductile behavior is attained. In the study of Sherif and Burrous (1969), Kaolin clay samples are heated under undrained conditions and tested in unconfined compression. It is reported that as temperature increases, the shear strength of the soil decreases predominantly as a result of increased pore water pressure and reduced effective stress.

Uchaipichat and Khalili (2009) also characterized the shear strength of unsaturated soils under nonisothermal conditions and suctions less than 300 kPa. They observed that the shear strength at critical state is unaffected by temperature, but the peak shear strength decreases with temperature due to thermal softening. They also observed that the positive effect of suction on the peak shear strength is greater than the negative effect of thermal softening. Alsherif and McCartney (2014) investigated the shear strength of unsaturated soils under very high suction magnitudes and nonisothermal conditions. Very dry conditions and high temperatures may be encountered during long-term heating of unsaturated soils in thermally active geotechnical systems. They observed that the change in shear strength with temperature depends on the sequence of heating and suction application, with an increase in peak shear strength after heating of specimens that are dried first, and a decrease in peak shear strength for specimens that are heated first before drying. Similar to Uchaipichat and Khalili (2009), they observed that suction has a greater effect on the peak shear strength than the temperature. The complex behavior of unsaturated soils indicates that there are more opportunities for research and development of constitutive models.

2.4.4. Effect of Temperature Changes on Thermally Induced Volume Change of Unsaturated Soils

The mechanisms of thermal volume change in unsaturated soils differ from those in saturated soils, as the differential expansion of the solids and pore water may not lead to the same magnitude of excess pore water pressures because of the presence of air in the pores. However, changes in temperature will still cause an expansion of the pore water, which may result in an increase in the degree of saturation and a decrease in suction. François and Laloui (2010) reported the development of an advanced thermo-hydro-mechanical (THM) oedometer in order to characterize the behavior of soils under combined non-isothermal and unsaturated conditions. The simultaneous control of temperature, suction and stress states within the sample required rigorous calibration. The authors thoroughly discussed the calibration of the device and presented some results of tests performed on a sandy silt. Uchaipichat and Khalili (2009) performed constant water content (undrained) heating tests on compacted silt at suctions up to 300 kPa, and measured a decrease in matric suction of 50% during heating from 25 to 60°C. Undrained heating of the specimen also led to elastic expansion along the loading-reloading curve. A decrease in suction would normally lead to expansion, but unsaturated soils show contraction during drained heating for stress states that are close to normally consolidated conditions. Stewart et al. (2014) reinterpreted the thermal volume change results of Uchaipichat and Khalili (2009) and Tang et al. (2008) in terms of effective stress, and observed that normally consolidated unsaturated soils show contraction while overconsolidated unsaturated soils show expansion, as shown in Figure 8. The reason for the contraction of unsaturated soils under normally consolidated conditions is still being investigated, but it may be due to a reduction in the yield stress during heating, which leaves the normally consolidated soil in an unstable state, leading to plastic collapse. This was clearly established by François and Laloui (2009) is their constitutive framework for the thermoplastic behavior of unsaturated soils.

2.4.5. Non-Uniformity in Soil Samples during Laboratory Tests

Another question in thermo-mechanical laboratory testing is how to address non-uniformity in samples for thermal conditions. The first reason of non-uniformity arises from temperature change applications where the samples are heated from the boundary that results in thermal gradients. During a drained test, an effort should be made to have a gradient as low as possible and also to allow the excess pore water pressure to drain. During thermo-mechanical laboratory tests, it is not possible to place a temperature sensor in the middle of the sample, in order not to disturb the samples. To solve this problem, preliminary calibration tests were performed by Cekerevac and Laloui (2005) to obtain the correlation between the measured temperature and the temperature inside the sample by using a temperature sensor in the middle of the specimen and in the triaxial cell (0.5 cm from the sample). From these tests a relationship between imposed temperature to the heater and the temperature in the middle of the sample is obtained for different confining pressures. The calibration test showed that the time lag between the beginning of the heating and the equilibration of the temperature in the middle of the sample was about 60 min for temperature steps of 10°C, which is assumed to be the required time to reach a uniform temperature distribution inside the sample, since the center of the sample is the most remote location from the heat source. To avoid the excess pore water pressure generation during drained heating tests, a heating rate of 10°C per 3 hours were used by several researchers (Burghignoli et al., 2000; Lingnau et al., 1996; Cekerevac and Laloui, 2005). This was confirmed by pore water pressure measurement during heating. In addition to temperature gradients and excess pore water pressure generation, a third factor affecting the uniformity of the samples is the boundary systems which are related to frictional layer at boundaries and have a significant impact on regular triaxial test.

2.4.6. Definition of Stress State and Effect of Temperature Changes on Preconsolidation Pressure

The definition of the stress state is another issue that could deserve further research. For example, the overconsolidation ratio is defined in terms of vertical stress conditions. However, during temperature changes, the dominant thermal directions are axially outward, which brings up the question on how to rationalize this difference. In the thermo-mechanical soil behavior the preconsolidation pressure is mostly used, which has more volumetric meaning. The oedometer test results of Campanella and Mitchell (1968) show that the compressibility curves at different temperatures have the same slope, with lower void ratios occurring at higher temperatures. Compression curve at a given temperature shifts to the left and down as the temperature increases. In other words, the preconsolidation pressure of the sample decreases with increasing temperature, but the compression index remains unchanged. This behavior has been confirmed by other researchers as well (Tidfors and Salfors, 1989; Boudali et al., 1994). It is also found that, higher the liquid limit, the greater the effect of temperature changes on the preconsolidation pressure (Tidfors and Salfors, 1989). In the same study, it is reported that the change in preconsolidation pressure depends on the magnitude of temperature change, clay content, water content, and depositional environment. Leroueil and Marques (1996) normalized the preconsolidation pressure values at different temperatures from various studies by the room temperature (20°C), as shown in Figure 9. They reported that the preconsolidation pressure decreases on average of 1%/°C between 5°C and 40°C.

2.4.7. Influence of Suction and Temperature Change on the Effective Preconsolidation Stress of Unsaturated Soils

Little experimental data exists analyzing the influence of suction on the effective preconsolidation stress of unsaturated soils (Salager et al., 2008; Uchaipichat and Khalili, 2009; François and Laloui, 2010). However, results from these tests suggest a hardening effect induced by increases in matric suction. This hardening effect is defined within the constitutive framework as an increase in the effective preconsolidation stress. Uchaipichat and Khalili (2009) performed temperature and suction controlled isotropic loading tests on a compacted silt (PI = 6) for different values of matric suction (0, 100, and 300 kPa) and temperature (25, 40, and 60°C). The effective preconsolidation pressure of each silt specimen was observed to remain constant for matric suction values less than that of the air entry suction, as expected for saturated soils. However, once the air entry suction was exceeded, the soil entered unsaturated conditions and the effective preconsolidation stress increased with increasing applied matric suction. Similar results have been obtained by Salager et al. (2008) who suggested a logarithmic relationship between effective preconsolidation stress and matric suction. The results of Uchaipichat and Khalili (2009) are reinterpreted in Figure 10, where the normalized effective preconsolidation pressure is compared to the normalized matric suction for three different temperatures. In addition to an increase in effective preconsolidation stress with matric suction, the rate of increase appears to be dependent on temperature.

3. Modelling the Thermo-Mechanical Response of Soils

Models reproducing the thermo-mechanical response of saturated clays at elevated temperatures have been published in various studies. Hueckel and Borsetto (1990) modified the critical state model by Schofield and Wroth (1968) to take into account the thermal effects. Their work focused on the thermo-mechanical behavior of the soil skeleton in drained conditions and was used to model the drained heating test results of three different clays (i.e. Boom clay, Pasquasia clay and Pontida silty clay) presented in Hueckel and Baldi (1990). According to their model, when the stress state is elastic, the elastic domain is assumed to shrink during heating and to expand during cooling. In the plastic state, thermal softening occurs simultaneously with the plastic strain hardening. They employed the thermal evolution of the yield limit at constant plastic strain condition to model the irreversible effect induced by temperature. Robinet et al. (1996) modelled thermo-elasto-plastic behavior of non-expansive saturated clays by using the modified Cam-Clay model and simulated the thermo-mechanical tests on Boom, Basin Parisien and Pontida clays (Baldi et al, 1988 and Belanteur, 1993). A cyclic thermo-viscoplastic model is developed by Modaressi and Laloui (1997) which includes thermal hardening and the evaluation of yield surfaces with temperature. Their results obtained from numerical modelling compare very well with the experimental results from Baldi et al. (1988). Cui et al. (2000) presented an elastoplastic model for saturated soils exposed to temperatures, with particular attention given to the effects of overconsolidation ratio on volume change. They validated their model by using the experimental results from various studies (Sultan, 1997; Baldi et al., 1988; Towhata et al., 1993). Graham et al. (2001) also introduced an extension of the modified Cam-Clay model which allows prediction of temperature change effects on volume change, pore water pressure generation and strength of normally and overconsolidated clays. They compared the predicted values with the experimental test performed by the authors (Tanaka and Graham, 1996; Tanaka et al., 1997). Laloui and Cekerevac (2003) developed a thermoplastic model where a one-parameter equation is used to capture the thermal evolution of the preconsolidation stress. Abuel-Naga et al. (2007b, 2009) introduced an isotropic thermo-elasto-plastic model that predicts the thermally induced volume changes in normally and overconsolidated saturated clays which consisted of loading yield limit and thermal yield limit. This model was then extended to the triaxial stress state in the context of critical state soil mechanics and modified Cam-Clay model (Abuel-Naga et al., 2009). Another thermo-mechanical soil behavior model from the family of thermal Cam-Clay models was developed by Hueckel et al. (2009) where influence of thermal variability on the coefficient of critical state and the angle of internal friction were emphasized. They discussed the importance of the thermal and mechanical history which was considered to be the most important factor in explaining the temperature dependent failure conditions.

Laloui and François (2009) presented the Advanced Constitutive Model for Environmental Geomechanics-Thermal effect (ACMEG-T) which summed up the previous developments in Modaressi and Laloui (1997), Laloui and Cekerevac (2003) and Laloui and Cekerevac (2008). The development of thermo-plastic strain starts when the stress point reaches the yield limit, as shown in Figure 11. The decrease of preconsolidation pressure with temperature, as mentioned in previous section, can be observed. The three main parameters governing the isotropic thermoplastic yield limit are defined as the degree of mobilized hardening, which enables the progressive evaluation of the isotropic yield limit during loading and unloading, a material parameter which controls the shape of the isotropic yield limit in the temperature-mean effective stress plane and the plastic compressibility modulus which is the slope of the plastic part of the volumetric strain-logarithm of mean effective stress curve.

The effect of temperature change on the volumetric response can be explained by Figure 12. In case 1, the temperature of an overconsolidated soil is being increased. During temperature increase, as the stress is within the yield limit, the volumetric strain will be thermo-elastic and dilatant. In case 2, the soil with a low overconsolidation ratio is first within the yield limit, however, with increase in temperature and a consequent decrease in preconsolidation pressure, the stress point reaches the yield limit. As a result, volumetric thermo-plastic strain is generated. Lastly, in case 3, thermal loading of a normally consolidated clay where the initial stress is already on the yield limit, a thermo-plastic volumetric strain occurs. During temperature increase, the stress point remains on the yield limit which induces thermal hardening. An illustration of the effects of temperature on the shape of the yield surface is shown in Figure 13.

The ACMEG-T model has been used to successfully simulate experimental results obtained in the literature. A numerical simulation of the results of Abuel-Naga et al. (2006), who performed drained heating-cooling cycles to Soft Bangkok clay specimens with different overconsolidation ratios (OCR = 1,2,4,8), using the ACMEG-T model is shown in Figure 14. There is a good agreement between the experimental and numerical results in terms of reversible dilation of highly overconsolidated clay and irreversible contraction of normally consolidated clays. The model has also been used to evaluate triaxial compression test results. A comparison between the drained triaxial compression test results of Abuel-Naga et al. (2006) performed on normally consolidated soft Bangkok clay with the results of the ACMEG-T model are shown in Figure 15. The experimental and numerical deviatoric stress results in Figure 15(a) show the thermal strengthening of the soft Bangkok clay that arises due to thermal consolidation. The model also matches well with the experimental volumetric strain results for soft Bangkok clay shown in Figure 15(b).

The effect of strain rate on the behavior fine grained soils is enhanced when temperature is increased. Laloui et al. (2008) improved the thermo-viscoplastic modelling of soils by taking advantage of the most recent understanding of the effects of temperature and strain rate on soils. In particular, modelling of the evolution of the vertical yield stress at any void ratio is made possible with the use of an advanced model for the dependence of vertical yield stress on temperature, as well as the use of the unique effective stress-strain-strain rate concept.

4. Effect of Temperature Change on Soil-Pile Interface

Data from model-scale tests on thermo-active piles have revealed the importance of considering the impact of soil-concrete interface behavior on soil-structure interaction. Goode et al. (2014) and Kramer and Basu (2014) performed model tests on concrete thermo-active piles in sand, and found that temperature had only a slight impact on the load-settlement behavior of the thermo-active pile when loaded axially to failure. This is in contrast to the observations of McCartney and Rosenberg (2010), who observed a clear increase in axial capacity with increasing temperature for semi-floating thermo-active piles in unsaturated silt.

There have been several experimental studies with the goal of understanding the effects of temperature on soil-pile interface shear strength for different soil types, including the development of novel testing approaches. Wang et al. (2011, 2012) performed uplift tests on thermo-active piles in sand, and observed that the sand-concrete interface shear strength decreases with temperature. The decrease may have been due to mobilization of shear stress due to thermal expansion during heating, which led to a lower shear strength when subsequently loaded. Xiao et al. (2014) performed temperature-controlled direct shear tests on compacted silt-concrete interfaces, and observed an increase in interface shear strength with temperature. This increase may have been due to thermally-induced drying of the unsaturated silt at the interface. In-situ thermal borehole shear tests were performed by Murphy and McCartney (2014), who evaluated the effect of temperature on the normalized soil-concrete interface. They observed no impact of temperature on the interface shear strength with a low plasticity clay as observed in Figure 16(a). They also observed that the normal stress was observed to have a much greater impact on the normalized shear stress-displacement curve than the temperature, as observed in Figures 16(b) and 16(c) for two different temperatures. Further research needs to be performed to understand issues at the interface, including dilation restraint, thermally induced water flow, and the role of the zone of influence of heating of the soil around the interface.

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Table 1: Methods used for thermo-mechanical laboratory testing

Testing approach	Study	Heating method	Notes
Thermal oedometer	Paaswell (1967)	Internal	Heating element in cell
	Plum and Esrig (1969)		Heating element in cell
	Towhata et al. (1993)		Heating element in cell
	Vega and McCartney (2014)		Heating coil within cell with backpressure
	Finn (1951)	External	Cell placed within a heated room
Thermal triaxial	Campanella and Mitchell (1968)	Internal	Heating of cell fluid with external heater
	Demars and Charles (1982)		Spiral heat exchanger tube in cell
	Burghignoli et al. (1992; 2000)		Spiral heat exchanger tube in cell
	Moritz (1995)		Sheets of heat foil mounted around specimen
	Kuntiwattanakul et al. (1995)		Heated an inner cell around specimen
	Saviddou and Britto (1995)		Heating of cell fluid with external heater

	Cekerevac et al. (2005)		Spiral heat exchanger tube in cell
	Uchaipichat and Khalili (2009)		Heating elements and cell fluid circulation
	Alsherif and McCartney (2014)		Heating elements and cell fluid circulation
	Coccia and McCartney (2014)		Heating elements and cell fluid circulation
	Baldi et al. (1988)	External	Flexible silicon rubber heater around cell
	Lignau et al. (1995)		Heater bands attached to outside of cell
	Delage et al. (2000)		Spiral heat exchanger tube around cell
	Abuel-Naga et al. (2007c)		Ring heaters attached to outside of cell
	Cui et al. (2009)		Spiral heat exchanger tube around cell
Thermo-hydro-mechanical cubical cell	Coccia and McCartney (2012)	Internal	Heating plates at top and bottom and loads applied to other four faces using air-filled bladders

Table 2: Effect of temperature changes on shear strength in various studies

Reference	**Type of Heating**	**Type of Shearing**	**Change in Shear Strength**
Abuel-Naga et al. (2007c)	Drained/Undrained	Undrained/drained	Increase
Burghignoli et al. (2000)	Drained	Undrained	Slight Increase
Tanaka et al. (1996; 1997)	Drained	Undrained	Increase
Cekerevac et al. (2005)	Drained	Drained	Slight Increase
Kuntiwattanakul et al. (1995)	Drained	Undrained	Increase
Houston et al. (1985)	Drained/Undrained	Undrained	Increase
Campanella and Mitchell (1968)	Drained	Undrained	Decrease
Hueckel and Baldi (1990)	Drained	Drained	Decrease
Moritz (1995)	Undrained	Undrained	Decrease
Sherif and Burrous (1969)	Undrained	Undrained	Decrease
Uchaipichat and Khalili (2009)	Drained	Drained	Decrease in peak shear strength, no change in shear strength at critical state
Alsherif and McCartney (2014)	Drained	Drained	Decrease for heating at low suction, increase for heating at high suction

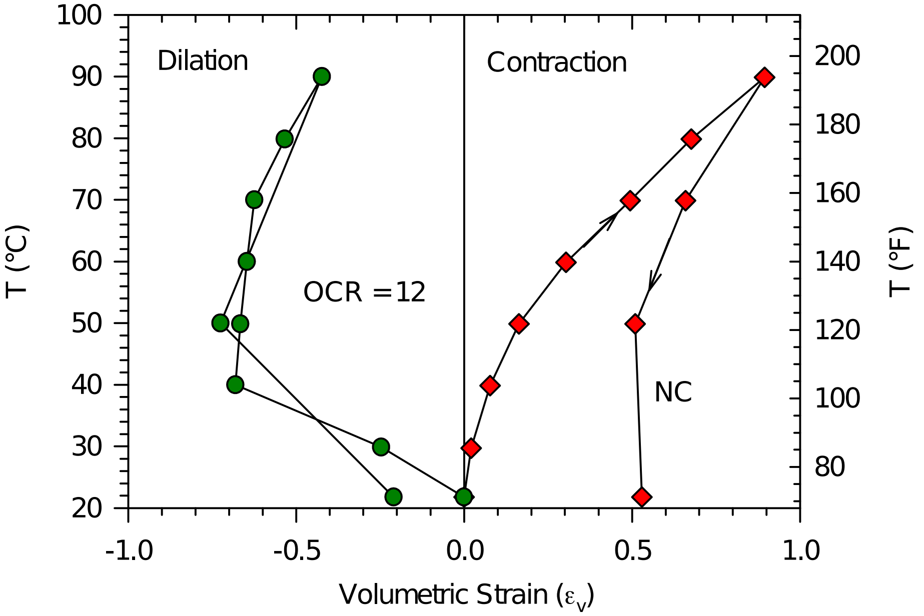


Figure 1. Volumetric strain generated during temperature changes for saturated Kaolin (Cekerevac, 2003)

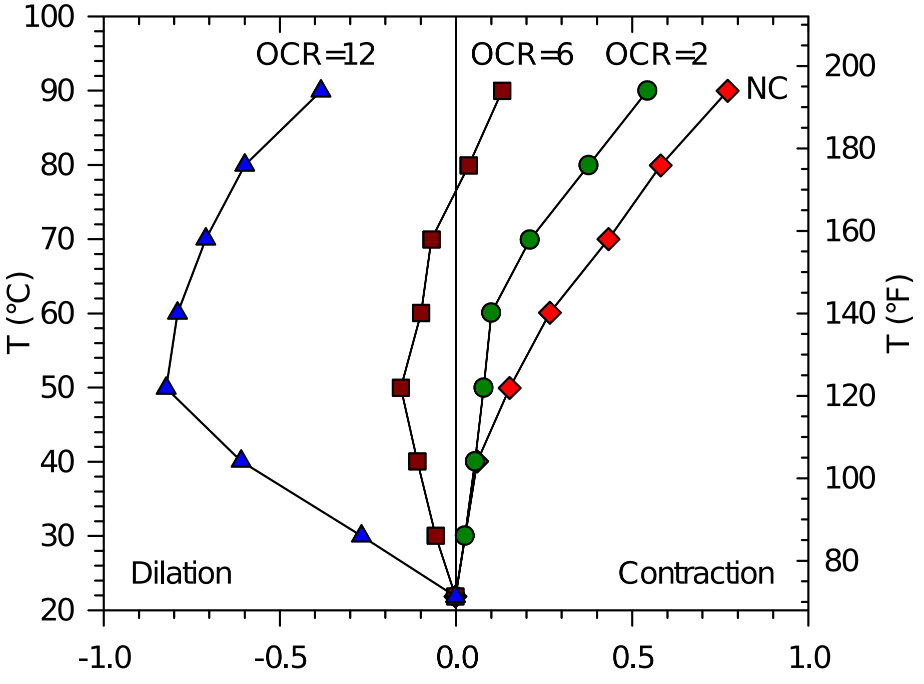
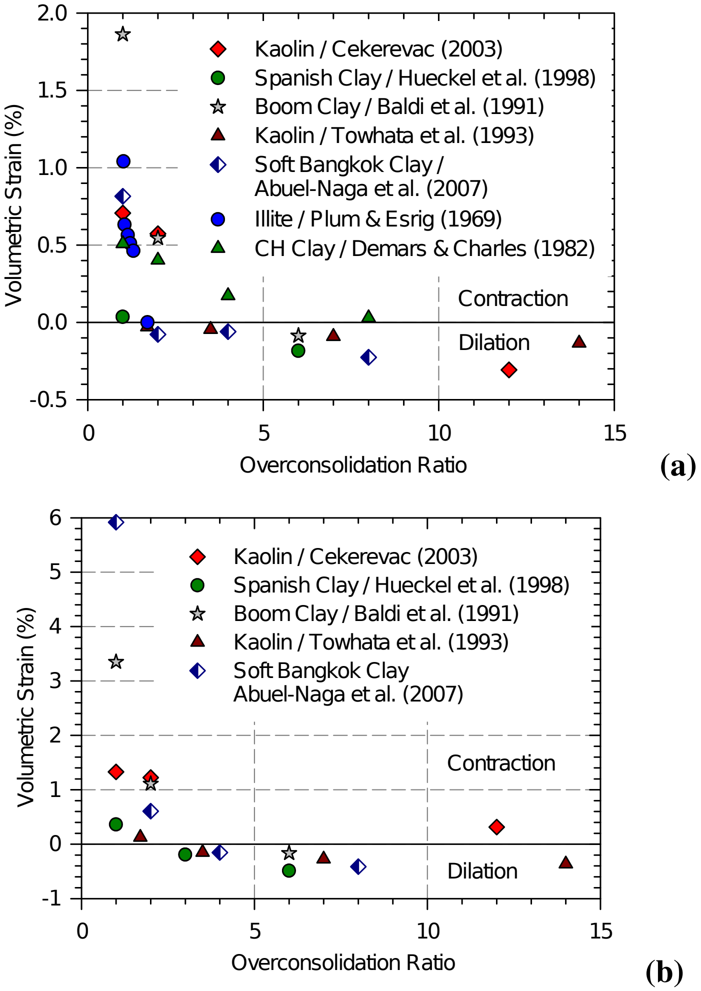


Figure 2: Effect of temperature change and OCR for saturated Kaolin (Cekerevac and Laloui, 2004)



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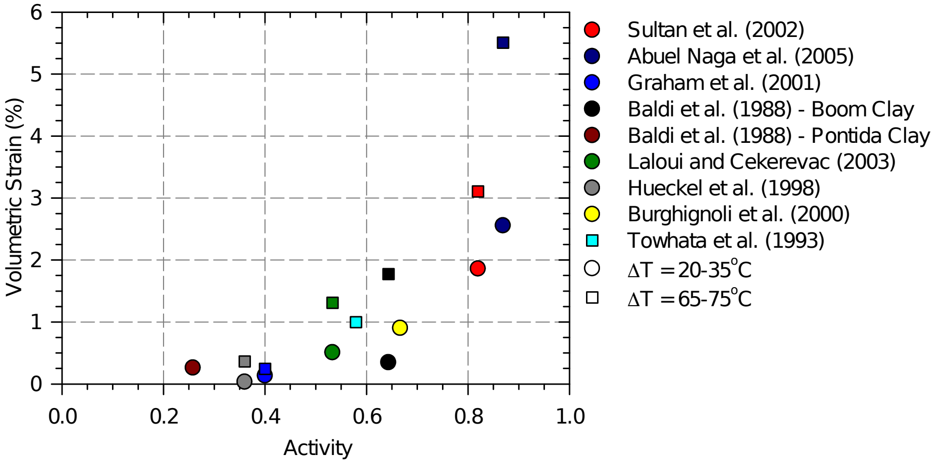

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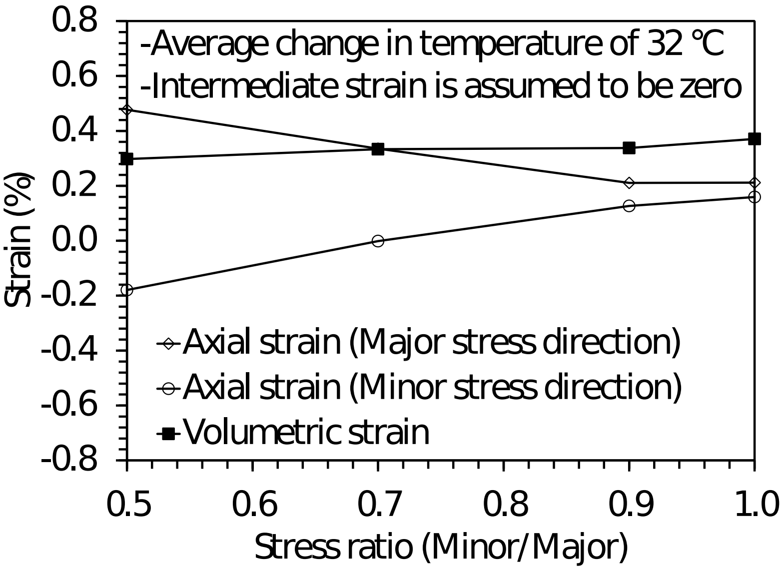

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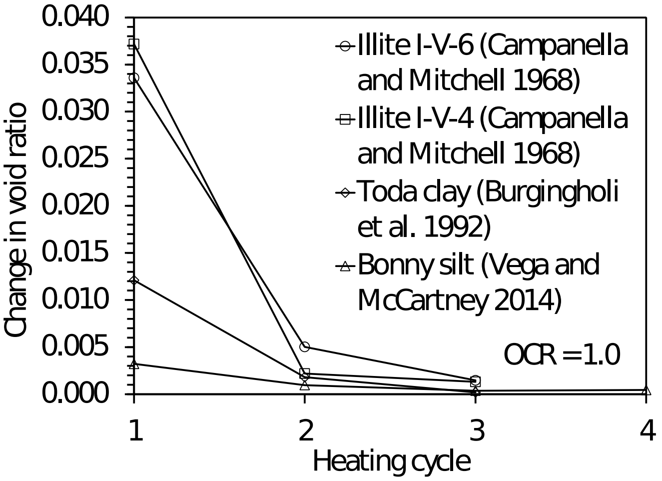

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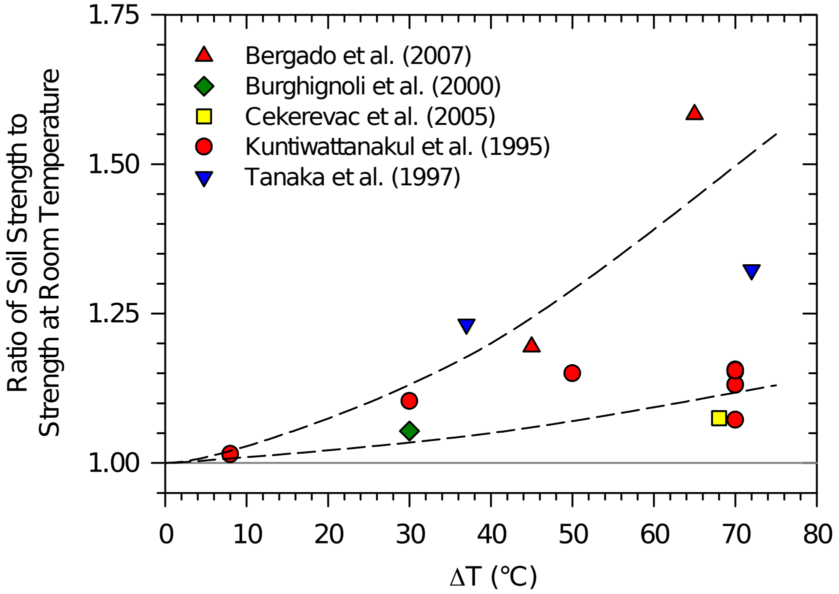

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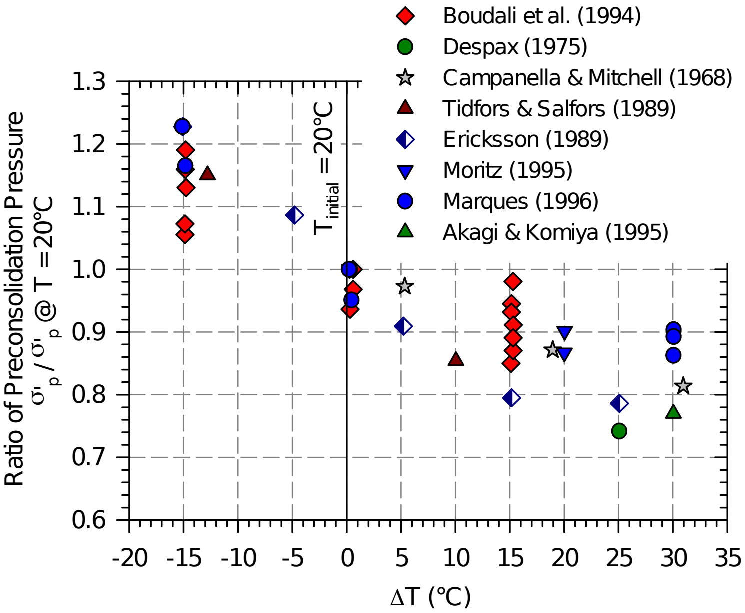

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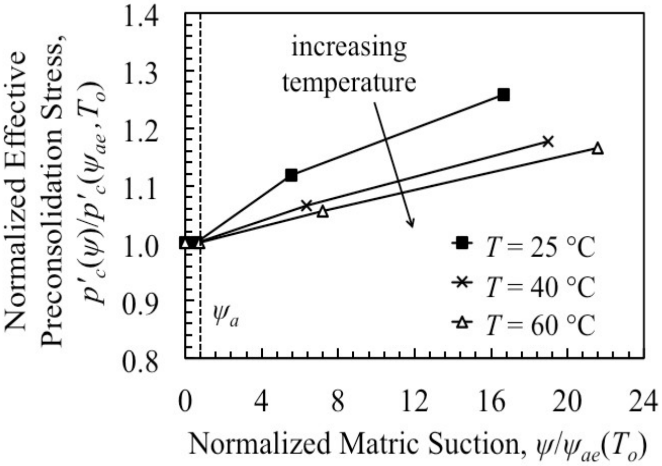

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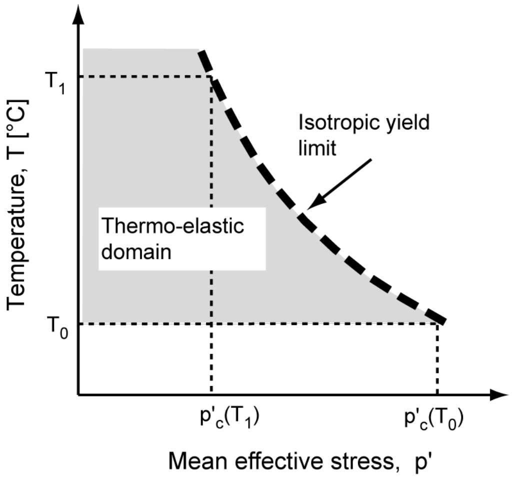
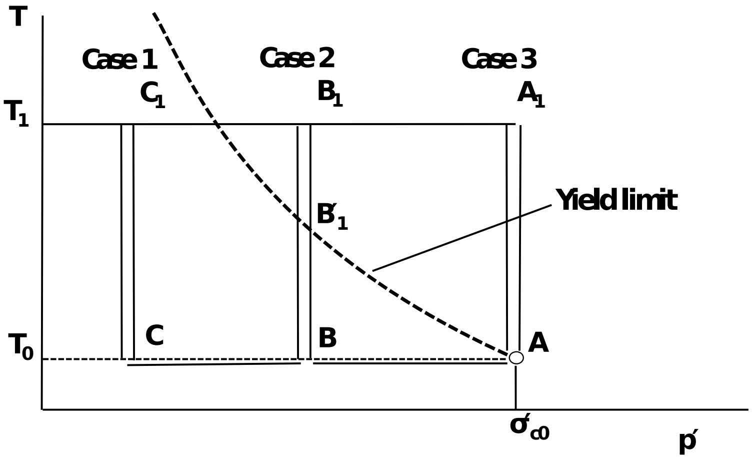


Figure 11: Isotropic thermoplastic yield limit (Laloui and Francois, 2009)



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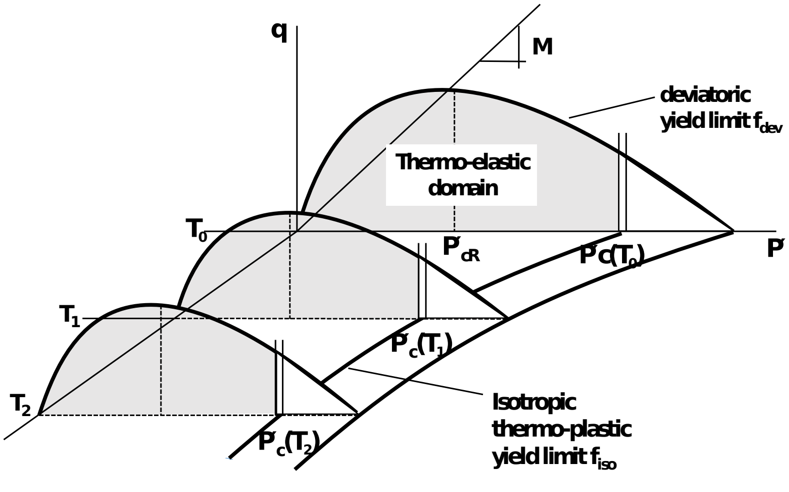

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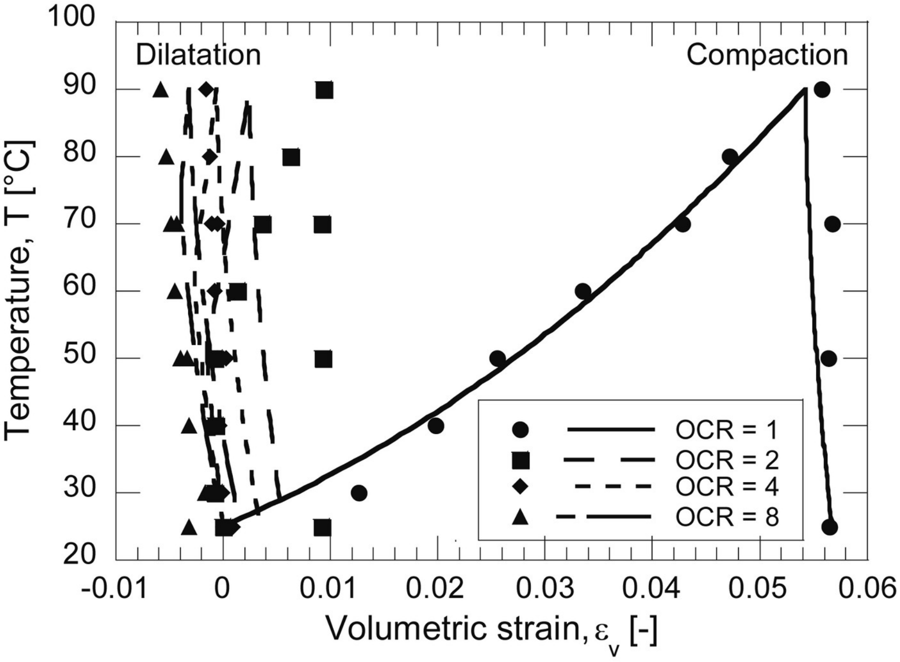

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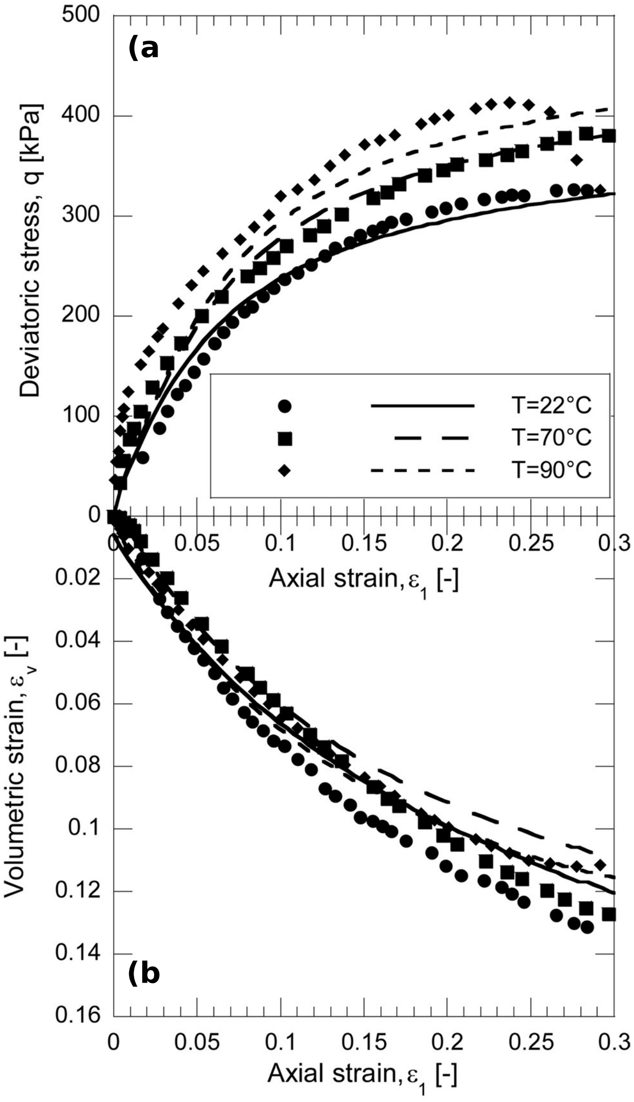

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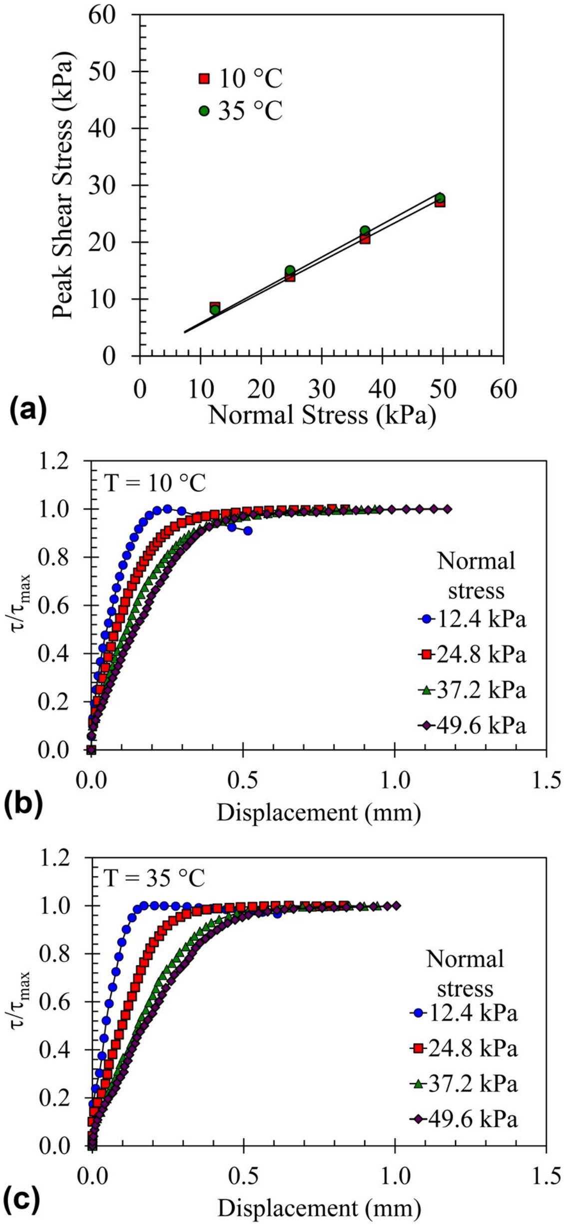

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