Thermal-mechanical Behaviour of Saturated Soil: A Review Study

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1 Introduction

The thermomechanical behaviour of soils is significantly important in some geo-engineering applications, such as design and installation of energy piles, radioactive waste disposal, burying of high-voltage cables and geothermal pipelines in soils, among others. These applications have led to the increased interest of the temperature effects on the engineering properties of soils. Therefore, in the past 30 years, a variety of laboratory tests have been conducted on different soils to investigate their thermo-mechanical properties, after the pioneering work by Campanella and Mitchell (1968). Based on the experimental observations, a great number of constitutive models were proposed to interpret the thermally induced volume change, yield mechanism and predict the temperature-related stress-strain relationship of soils. This main purpose of this work is to present the different temperature effects observed in soils.

2 Thermal behaviour

In this section, the thermally induced volume change, excess pore water pressure generation for saturated soils will be included. In addition, the temperature effects on the mechanical response, such as compressibility and shear strength of soils are presented.

2.1 Thermally induced volume change

The thermally induced volumetric behaviour of soils has a significant influence in many geotechnical engineering problems such as the landfill cover system, pipeline engineering, geothermal energy development and pavement engineering (Towhata, Kuntiwattanaku, Seko, & Ohishi, 1993). The following description concerns the thermally induced volume change of clay and sand. The difference of thermally induced volume change in clay and sand are emphasized.

Saturated clayey soil

Temperature strongly affects the behaviour of clays through its influence on free and adsorbed water. Fig. 1 depicts the thermal response of Boom clay subjected to thermal loadings (22–100 °C) at various ORC values (ORC=1, 2, and 12) or thermal loading-unloading cycles (22–100–27 °C) at constant isotropic stress. Figure 1 shows that the sample contracts during the heating phase with a non-linear volume variation. During cooling, on the contrary, a relatively linear behaviour results in volume increase regardless of the OCR.

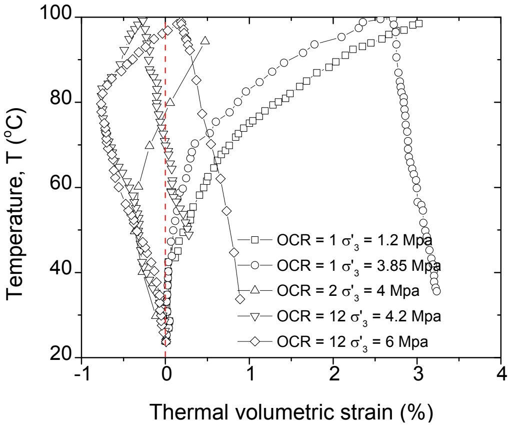

Fig. 1. Thermal volumetric strain of Boom clay during drained heating from 22 to 100 °f under different confining stresses (after Sultan, Delage, and Cui (2002))

Sandy soil

Most of the past laboratory tests of the thermal behaviour of soils have been concentrated in fine-graded soils such as clay and silt (H. Abuel-Naga, Bergado, Bouazza, & Ramana, 2007; Campanella & Mitchell, 1968; Cui, Sultan, & Delage, 2000), but in last few years increasing attention has been paid to experimental research into the thermal behaviour of granular materials (Ng, Wang, & Zhou, 2016; Vega & McCartney, 2014; Zhou, Ng, & Wang, 2017), because sand is often encountered in the energy-related engineering applications, for example, hydrocarbon extraction from oil-bearing sands.

Ng et al. (2016) investigated the thermally induced volume change of soil skeleton of saturated Toyoura sand by using a temperature-controlled triaxial apparatus. Fig. 2(a) shows the heating-induced volume changes of sand with different densities at 200 kPa, it can be observed that, during the first heating process, loose and medium dense specimens showed contractive strains of approximately 0·15% and 0·05% respectively as the temperature rose from 23 to 35°C, while the responses of specimens with different densities were almost reversible with heating expansion and cooling contraction during the second thermal cycle (see Fig. 2(b)). The experimental investigation reveals that sand response becomes stiffer after the first thermal cycle, and exhibits an elastic response to thermal loading-unloading within a certain temperature range.

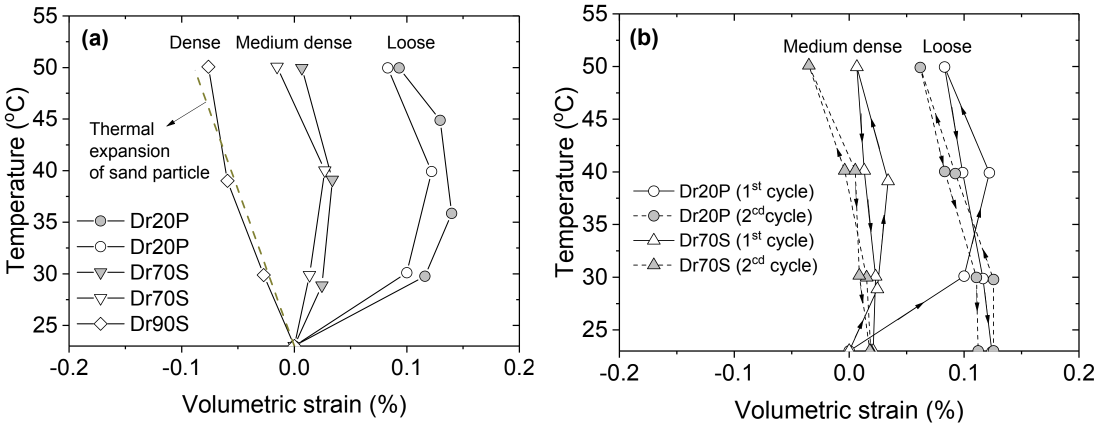

Fig. 2: Heating-induced volume changes of sand with different densities at 200 kPa (a) during the thermal loading, and (b) during thermal loading-unloading cycles (after Ng et al. (2016))

2.2 Excess pore pressure generation

It is well known that undrained heating of saturated soils leads to excess pore water pressure generation and that cyclic undrained thermal loads result in accumulation of excess pore water pressure due to the differential expansion of the pore water and soil solids (Campanella & Mitchell, 1968).

Saturated clayey soil

Extensive experimental works concerning the thermally induced pore water pressure in the clayey soil can be found in the literature (Hossam M. Abuel-Naga, Bergado, & Bouazza, 2007; Burghignoli, Desideri, & Miliziano, 2000; T. Hueckel & Pellegrini, 1992; Plum & Esrig, 1969; Uchaipichat & Khalili, 2009). Particularly, Ghaaowd, Takai, Katsumi, and McCartney (2015) summarized the above mentioned experimental data and analysis the thermally induced pore water pressure for various type of soils.

Figure 3 shows the excess pore water pressure induced by the change in the temperature for 13 normally consolidated soil specimens along with the initial mean effective stress. It reveals that the excess pore water pressure increases linearly with the temperature increase. Additionally, the initial mean effective stress plays an important role, as the stiffness of the soil skeleton is expected to increase with increasing mean effective stress which may affect the pore water pressure generation during heating.

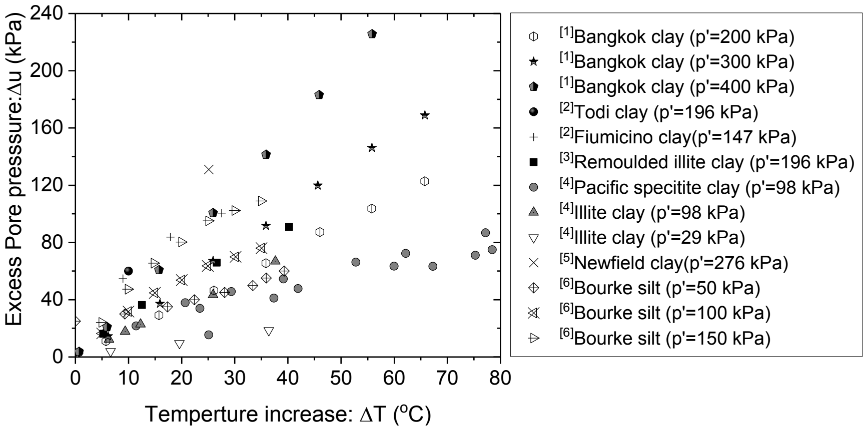

Fig. 3: Effect of temperature change on the change in pore water pressure for different soil specimens, [1]Abuel-Naga et al. (2007b);[2]Burghignoli et al. (2000) [3] Campanella and Mitchell (1968); [4] Houston et al. (1985); [5]Plum and Esrig (1969); [6]Uchaipichat & Khalili (2009) (after Ghaaowd et al. , 2015)

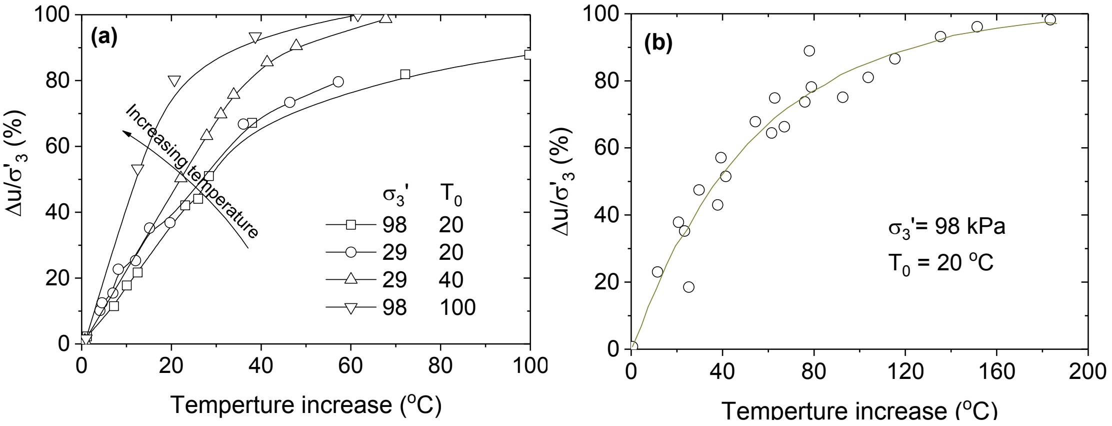

Fig. 4: (a) Normalized excess pore water pressure with temperature increase for (a) Illite clay and (b) Pacific specitite clay (after Houston, Houston, and Williams (1985))

For better understanding the effect of pore water pressure generation on the soil behaviour in undrained heating, the results obtained by Houston et al. (1985) for two types of clays are replotted in Fig. 4, where the relationships between the change in normalized pore pressure with temperature for illite clay and Pacific specitite clay are summarized. As shown in Fig. 4(a), the initial slope of the curve is related to the testing temperature, and the change of pore water pressure with temperature depends strongly on the stiffness characteristic properties of the soils. The increased steepness of the curve with increased temperature reflects an occurrence of a *thermal consolidation phenomenon* or *quasi pre-consolidation*, which is caused by the dissipation of thermally induced pore water pressure and rearrangement of the soil fabric in undrained heating condition. Similar behaviour for normally consolidated soft Bangkok clay specimens was reported by H. Abuel-Naga et al. (2006) in oedometer tests. Noted that the rate of pore water pressure generation due to undrained heating in Pacific specitite clay (see Fig. 4(b)) is much lower than that in the Illite clay. This is due to the plastic index of Pacific specitite clay (I_P = 109) is much higher than that of Illite clay (I_P = 47).

Sandy soil

There are only a few reported laboratory studies concerning the thermally induced pore water pressure generated in the sand. Agar (1986) investigated the pore pressure response of oil Athabasca sand to undrained heating in tests carried out using both the oedometer and the triaxial apparatus. The effect of temperature change on the change in pore water pressure for Athabasca oil sand is shown in Fig. 5, which reveals that unlike the linear increase of pore pressure in clayey soils as shown in Fig. 4, the pore pressure response due to undrained heating is nonlinear both in oedometer and triaxial tests.

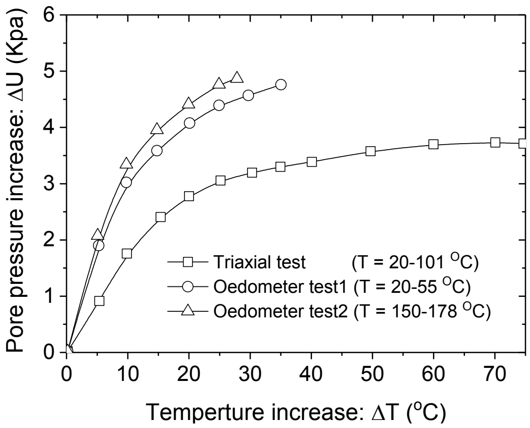

Fig. 5: Effect of temperature change on the change in pore water pressure for Athabasca oil sand (after Agar 1986)

3 Mechanical behaviour

In the following, the effects of temperature on the mechanical behaviour of the soils are illustrated. Attention will be focused on the effects of temperature on compressibility, and shear strength.

3.1 Preconsolidated pressure

Preconsolidation pressure, σ'_c, is considered as the pseudo-elastic limit which separates elastic pre-yield from plastic postyield behaviour in isotropic or oedometric conditions. It is evaluated as the stress value at the intersection of the two linear parts of the compression curves. The temperature effects on the pre-consolidation pressure have been extensively studied by carrying out oedometer tests and triaxial tests.

Among the first study of this area, Campanella and Mitchell (1968) investigated the influence of temperature on the isotropic compressibility of normally consolidated remolded illitic clay; as shown in Fig. 6, the compression curves shift to left, with an approximately identical slope (λ), as temperature increases, which implies that the pre-consolidation pressure decreases with temperature. However, the compression indices (*Cc*) of remolded illitic clay seemed unaffected by temperature. Similar results were obtained by Burghignoli et al. (2000) in isotropic compression tests.

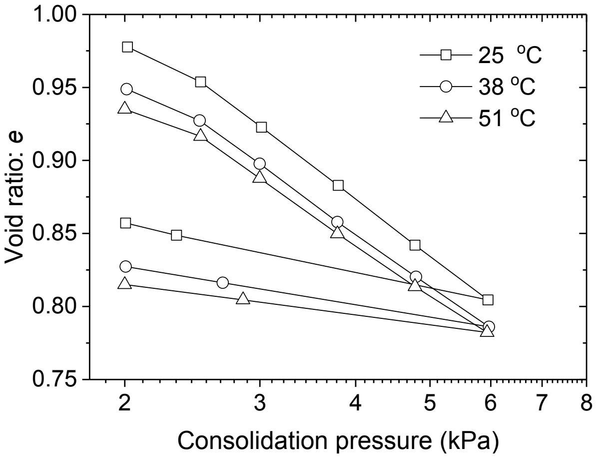

Fig. 6: Effect of temperature on isotropic consolidation behaviour of saturated illite (after Campanella and Mitchell (1968))

The effects of temperature on the preconsolidated pressure of saturated clays were experimentally studied by many authors. The same conclusion that the pre-consolidation pressure decreases non-linearly with increased temperature has been drawn from their experimental investigations. For example, Tidfors and Sällfors (1989) reported that the preconsolidated pressure of various type of Swedish clays decreases linearly with temperature increase from 0. Similar results were reported by Boudali (1994) for three medium plasticity clays in a smaller range of temperature (5–35 °C). Cekerevac and Laloui (2004) summarized the tests results obtained from this literature. The temperature effects on the preconsolidated pressure for various type of soils is shown in Fig. 7.

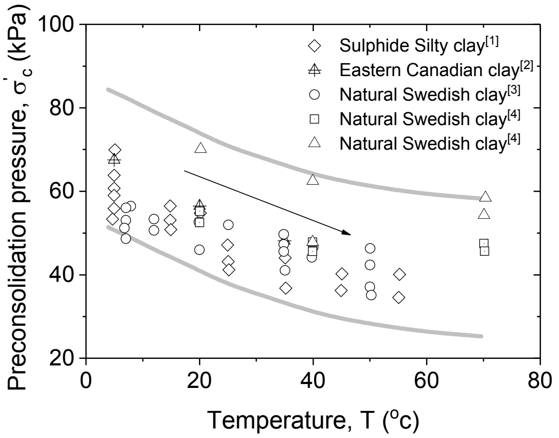

Fig. 7: Influence of temperature on preconsolidated pressure, data collected from references [1] Eriksson (1989); [2] Boudali (1994); [3] Tidfors and Sällfors (1989); [4] Moritz (1995)(after Cekerevac and Laloui (2004))

3.2 Shear strength

In this section, the temperature effects on the shear strength of both saturated and unsaturated soils are illustrated.

Saturated clayey soils

Despite temperature effects on the shear strength of saturated clayey soils have been extensively studied, the influence of temperature on shear strength remains unresolved. Previous experimental research reveals that the temperature effect on shear strength is of the discrepancy. Some laboratory results reported by previous studies show that an increase in temperature can cause an increase in shear strength of saturated soils in drained and undrained conditions (Hossam M Abuel-Naga, Bergado, & Lim, 2007; Cekerevac & Laloui, 2004; Graham, Tanaka, Crilly, & Alfaro, 2001; T. Hueckel, Francois, & Laloui, 2011; kuntiwattanakul, Towhata, Ohishi, & Seko, 1995). Other studies show a reduction of the strength in elevated temperatures (Ghahremannejad, 2003; T Hueckel & Borsetto, 1990; Lingnau, Graham, & Tanaka, 1995; Moritz, 1995). There are studies suggesting that an increase in temperature does not affect the strength of soils (Burghignoli et al., 2000; Cekerevac & Laloui, 2004; Graham et al., 2001; Towhata et al., 1993)

Abuel-Naga et al., (2007b) investigated the temperature effects on the shear strength of soft Bangkok clay. Fig. 8(a) shows the undrained shear strength results of isotropic normally consolidated soft Bangkok clay with preconsolidated pressure p'_c of 200 kPa that were subjected to different drained hearing levels and hearing cycle. The result shows that the peak deviatoric stress increases with increase in soil temperature. It is expected that when normally consolidated soil experienced temperature cycling, the drained thermal consolidation may occur, and leads to an increase in shear strength. This observation is supported by many researchers (Burghignoli et al., 2000; Houston et al., 1985; kuntiwattanakul et al., 1995; Trani, Bergado, & Abuel-Naga, 2013). Additionally, the excess pore pressure decreases with the soil temperature increases for all specimen (see Fig. 8(b)).

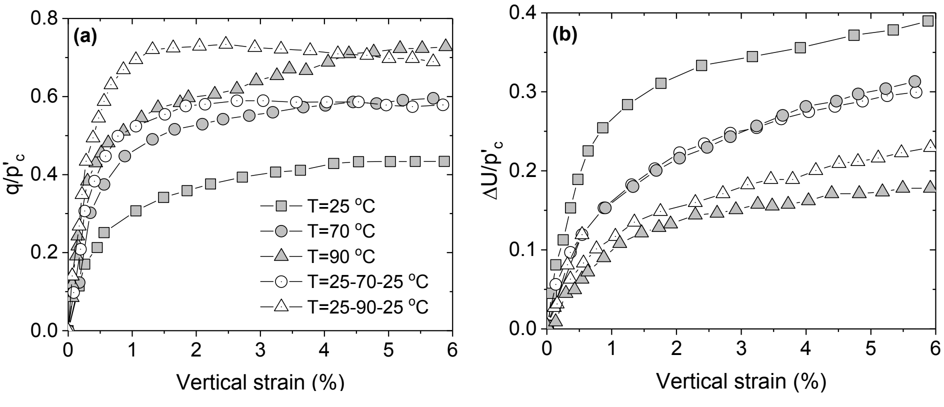

Fig. 8: Undrained triaxial compression test results on normally consolidated soil at different temperatures and temperature history (p'_c = 200 kPa), (a) Normalised deviatoric stress, and (b) Normalised excess pore water pressure (after H. Abuel-Naga et al. (2007))

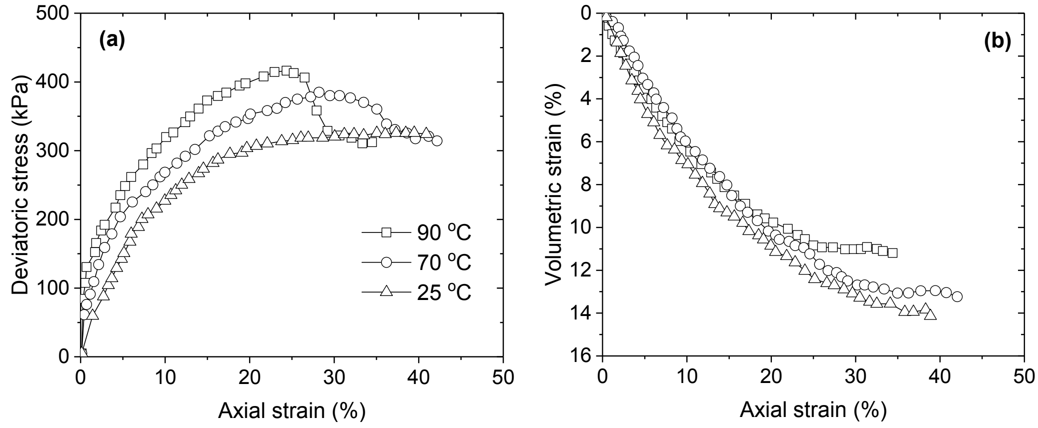

Fig. 9: Drained triaxial compression test results on normally consolidated soil at different temperatures (p'_c =300 kPa) (after H. Abuel-Naga et al. (2006))

The results of the drained compression triaxial shear tests conducted on normally consolidated soil specimens at 300 kPa drained heated to different temperatures are plotted in Fig. 9. The results show that the specimens sheared at higher temperatures obtained higher peak deviatoric stresses. Noted that, at large strains, the residual deviatoric stress of the soil is independent of temperature. Trani et al. (2013) extended this study by adding two tests with specimens subjected to heating-cooling cycling and the pointed out that heating-cooling cycling can increase the deviatoric stress but cannot influence the residual deviatoric stress. Also, the soil specimens tested at room temperature exhibits strain hardening behaviour, while other specimen subjected thermally drained heating exhibit strain softening. Additionally, the specimens sheared at higher temperature have lower volumetric strain. Similar results were obtained by Cekerevac and Laloui (2004) for NC CM clay specimens sheared under a drained condition at an elevated temperature of 22 and 90 ^{o}C.

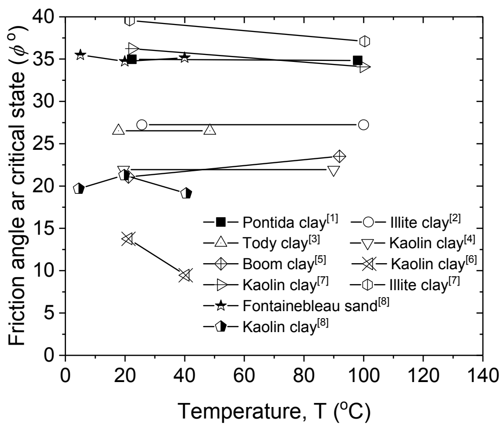

Fig. 10: Effect of temperature on friction angle at critical state, (data collected from [1]Hueckel & Baldi 1990 ;[2] Tomasz Hueckel and Pellegrini (1991); [3] Burghignoli et al. (2000); [4]Graham et al. (2001); [5]Cekerevac and Laloui (2004); [6]Robinet, Rahbaoui, Plas, and Lebon (1996); [7]Ghahremannejad (2003); [8]Yavari, Tang, Pereira, and Hassen (2016)

Figure 10 summarized the temperature effects on the friction angle at the critical state, it reveals that the effect of temperature on most soils (except Kaolin) is quite small, and the friction angle at critical state may increase or decrease or remain independent with elevated temperature.

Sandy soil

The temperature effect on the shear strength of sand is similar to that of clay. Saada, Bonnet, and Bouvard (1996) studied the thermo-mechanical behaviour of casting sand at variety large range of temperature. Experimental results of triaxial tests at a constant confining pressure of 0.6 Mpa and different temperature are presented in Fig. 11. The results show that, for specimens at a lower temperature range (25 °C-100 °C), the axial stress continuously increase with axial strain and exhibit strain hardening behaviour, while strain softening behaviour is observed for specimens subjected to relatively high temperature (150 °C-300 °C).

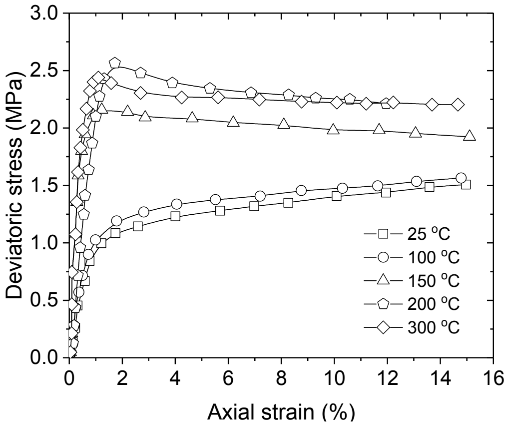

Fig. 11: Drained compression triaxial test results at a different temperature of casting sand (after Saada et al. (1996))

It is noteworthy that there are only very few experimental investigations of temperature effects on the shear strength of sandy soil, so the experimental evidence is not enough to state that elevated temperature can increase or decrease the shear strength of sand. More experimental investigations in this area are required to resolve this uncertainty.

4 Summary

During drained heating, normally consolidated saturated clayey soil exhibit elastoplastic thermal contraction. The contraction decreases with OCR increase. Heavily-over-consolidated soils exhibit elastic expansion; Thermal loading can cause the change of excess pore pressure and matric suction in saturated soil and unsaturated soil, respectively. The thermally induced excess pore water change is linear in saturated clayey soils, while it is nonlinear for sand; The preconsolidated pressure of both saturated and unsaturated soil decreases with elevated temperature, while the compression and swelling indexes are independent of temperature. The friction angle at critical state can either increase or decrease (or remain independent) with temperature. The friction angle variation with temperature can be significantly influenced by the thermal loading history, the testing method adopted, and the soil used. Experimental work on thermal effects of sand are very few, more laboratory investigations are required to clarify the thermal effects on the sand.

Reference

Abuel-Naga, H., Bergado, D., Bouazza, A., & Ramana, G. (2007)
Volume change behaviour of saturated clays under drained heating conditions: experimental results and constitutive modeling, Can. Geotech. J. Vol 44, No.8, 942-956.

Abuel-Naga, H., Bergado, D., Ramana, G., Grino, L., Rujivipat, P., Thet, Y. (2006)
Experimental evaluation of engineering behavior of soft Bangkok clay under elevated temperature. J. Geotech. Geoenviron. Vol 132, No. 7, 902-910.

Abuel-Naga, H. M., Bergado, D. T., & Bouazza, A. (2007)
Thermally induced volume change and excess pore water pressure of soft Bangkok clay. Eng. Geol., Vol 89, No.1-2, 144-154.

Abuel-Naga, H. M., Bergado, D. T., & Lim, B. F. (2007)
Effect of temperature on shear strength and yielding behavior of soft Bangkok clay. Soils Found., Vol 47, No.3, 423-436.

Boudali, M. (1994)
Viscous behaviour of natural clays. Paper presented at the Proc. 13th Int. Conf. on SMFE.

Burghignoli, A., Desideri, A., & Miliziano, S. (2000)
A laboratory study on the thermomechanical behaviour of clayey soils. Can. Geotech. J., Vol 37, No. 4, 764-780.

Campanella, R. G., & Mitchell, J. K. (1968)
Influence of temperature variations on soil behavior. J. Soil Mech. Found. Div. Vol 94, No. SM3, 709-734.

Cekerevac, C., & Laloui, L. (2004)
Experimental study of thermal effects on the mechanical behaviour of a clay Int. J. Numer. Anal. Methods Geomech, Vol 28, No. (3), 209-228.

Cui, Y. J., Sultan, N., & Delage, P. (2000)
A thermomechanical model for saturated clays. Can. Geotech. J., Vol 37, No. (3), 607-620.

Eriksson, L. (1989).
Temperature effects on consolidation properties of sulphide clays. Paper presented at the International Conference on Soil Mechanics and Foundation Engineering: 13/08/1989-18/08/1989.

Ghaaowd, I., Takai, A., Katsumi, T., & McCartney, J. S. (2017)
Pore water pressure prediction for undrained heating of soils. Environ. Geotech., Vol 4, No. (2), 70-78.

Ghahremannejad, B. (2003)
Thermo-mechanical behaviour of two reconstituted clays. Phd thesis.

Graham, J., Tanaka, N., Crilly, T., & Alfaro, M. (2001)
Modified Cam-Clay modelling of temperature effects in clays. Can. Geotech. J., Vol 38, No. (3), 608-621.

Houston, S. L., Houston, W. N., & Williams, N. D. (1985)
Thermo-mechanical behavior of seafloor sediments. J. of Geotech. Engi., Vol 111, No. (11), 1249-1263.

Hueckel, T., & Borsetto, M. (1990)
Thermoplasticity of saturated soils and shales: constitutive equations. J. of Geotech. Engi., Vol 116, No. 12, 1765-1777.

Hueckel, T., Francois, B., & Laloui, L. (2011)
Temperature-dependent internal friction of clay in a cylindrical heat source problem. Géotechnique, Vol 61, No. 10, 831-844.
Hueckel, T., & Pellegrini, R. (1991)
Thermoplastic modeling of undrained failure of saturated clay due to heating. Soils and Found., Vol 31, No. 3, 1-16.
Hueckel, T., & Pellegrini, R. (1992)
Effective stress and water pressure in saturated clays during heating–cooling cycles. Can. Geotech. J., Vol 29, No. 6, 1095-1102.
kuntiwattanakul, P., Towhata, I., Ohishi, K., & Seko, I. (1995)
Temperature effects on undrained shear characteristics of clay. Soils and Found., Vol 35, No. 1, 147-162.
Laloui, L. (2001).
Thermo-mechanical behaviour of soils. Revue française de génie civil, Vol 5 No. 6, 809-843.
Lingnau, B., Graham, J., & Tanaka, N. (1995)
Isothermal modeling of sand–bentonite mixtures at elevated temperatures. Can. Geotech. J., Vol 32, No. 1, 78-88.
Moritz, L. (1995)
Geotechnical properties of clay at elevated temperatures:Swedish Geotechnical Institute Linköping, (Vol. 47)Sweden.
Ng, C. W. W., Wang, S., & Zhou, C. (2016).
Volume change behaviour of saturated sand under thermal cycles. Géotech. Lett., Vol 6, No. (2), 124-131.
Plum, L., & Esrig, M. (1969)
Some temperature effects on soil compressibility and pore water pressure. Special Report-Highway Research Board(103), 231.
Robinet, J.-C., Rahbaoui, A., Plas, F., & Lebon, P. (1996)
A constitutive thermomechanical model for saturated clays. Eng. Geol., Vol 41, No. 1-4, 145-169.
Saada, R. A., Bonnet, G., & Bouvard, D. (1996)
Thermomechanical behavior of casting sands: Experiments and elastoplastic modeling Int. J. Plast., Vol 12, No. 3, 273-294.
Sultan, N., Delage, P., & Cui, Y. (2002)
Temperature effects on the volume change behaviour of Boom clay. Eng. Geol., Vol 64, No. 2, 135-145.
Tidfors, M., & Sällfors, G. (1989)
Temperature effect on preconsolidation pressure. Geotech. Test. J., Vol 12, No. 1, 93-97.
Towhata, I., Kuntiwattanaku, P., Seko, I., & Ohishi, K. (1993).
Volume change of clays induced by heating as observed in consolidation tests. Soils and Found., Vol 33, No. 4, 170-183.
Trani, L., Bergado, D., & Abuel-Naga, H. (2013).
Thermo-mechanical behavior of normally consolidated soft Bangkok clay. Int. J. Geotech. Eng., Vol 4, No. 1, 31-44.
Uchaipichat, A., & Khalili, N. (2009).
Experimental investigation of thermo-hydro-mechanical behaviour of an unsaturated silt. Géotechnique, Vol 59, No. 4, 339-353.
Vega, A., & McCartney, J. S. (2014).
Cyclic heating effects on thermal volume change of silt. Environ. Geotech., Vol 2, No. 5, 257-268.
Yavari, N., Tang, A. M., Pereira, J.-M., & Hassen, G. (2016).
Effect of temperature on the shear strength of soils and the soil–structure interface. Can. Geotech. J., Vol 53, No. 7, 1186-1194.
Zhou, C., Ng, C. W. W., & Wang, S. (2017).
Modelling volume changes of sand under thermal loads: a preliminary attempt. Géotech. Lett., Vol 7, No. 1, 68-72.