THERMAL CONSOLIDATION OF SOFT BANGKOK CLAY

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ABSTRACT: Understanding the thermo-mechanical behavior of saturated fine grained soils has become a very important topic whenever the geotechnical problems involve thermal effects. Previous research works in literature show that by subjecting the saturated fine-grained soils to temperature less than water boiling point volumetric and shear strength changes are induced. The thermally induced changes have been attributed to the physico-chemical change at the microscopic level. The aim of this research is to study the thermo-mechanical behavior of natural soft Bangkok clay, with temperature up to 90^oC. Intensive laboratory tests using modified oedometer apparatus were conducted to investigate this behavior. The testing program was directed to study the effect of heat on the thermally induced volume change at different temperature and stress conditions, the thermal evolution of the preconsolidation pressure, the induced overconsolidation behavior after heating/cooling cycle, and the effect of temperature on the hydraulic conductivity. The experiments carried out on soft Bangkok clay provided some additional useful data on the thermo-mechanical behavior of the soft deposits. The results of this research work have been compared with those in literature with different clay types to generalize the thermo-mechanical behavior of the saturated clays.

Key Words: Thermo-mechanics, clay, temperature, volume change.

INTRODUCTION

The clear understanding for the effect of temperature on the soil behavior becomes mandatory for many engineering applications such as design of nuclear waste disposal facilities (Davies and Banerjee 1980), buried electrical cables (Abdel-Hadi and Mitchell 1981), oil and gas pipe lines (Slegel and Davis 1977), and ground heat energy storage (Moritz 1995). These applications have led to increasing considerations of the temperature effects on the engineering properties of soils and have made the thermo-mechanical behavior of soils as one of the major issues in modern soil mechanics.

Interest in this topic dates back from the sixties, when the first conference concerning the effect of temperature and heat on engineering behavior of soils was held in Washington D.C., U.S.A. in 1969. The temperature ranges used in the early research works were limited to the range of 10 to 50^oC. This limitation was understood, because the major concern at that time was to study the effect of temperature change on the volumetric and strength parameters of the soil specimen during sampling and transportation to the laboratory. However, when the research studies were directed to design safe radioactive disposal in clay formations, understanding of the thermo-mechanical behavior at temperatures up to 100^oC become important.

Previous research works in literature show that subjecting the saturated fine-grained soils to temperature less than water boiling point induces volumetric and shear strength changes. In the absence of evidence of change in mineralogy upon heating the saturated fine-grained soils up to 90^oC (Graham et al. 2001), all the previous research works have attributed the thermo-mechanical behavior to the changes in the thermally induced physico-chemical forces between the clay particles upon heating.

Sridharan and Venkatappa Rao (1973), Morgenstern and Balasubramonian (1980), and Mitchell (1993) found that changes in pore-fluid valence, concentration, permittivity, and temperature have significant effect on the physico-chemical forces between the clay particles which control the mechanical behavior of the saturated fine-grained soil Therefore, it is evident that changes in the pore-fluid temperature may alter the shear strength behavior and induce volumetric strain.

Laloui (2001) has presented a review of the research work on thermo-mechanical behavior of the saturated fine-grained soils as summarized below: 1) The thermally induced volumetric changes depend on the stress history condition (Baldi et al. 1988; Towhata et al. 1993). It is irreversible contraction for the normally consolidated clays while it becomes reversible expansion for the highly overconsolidated clays. 2) The normally consolidated clays show higher preconsolidation pressure upon reloading after subjecting to heating cooling cycle (Towhata et al. 1993; Robinet et al. 1996; Burghignoli et al. 2000). 3) Different clay types show reduction of the elastic domain at elevated temperature (Cekerevac et al. 2002). 4) The hydraulic permeability of the clays increases with temperature (Towhata et al. 1993; Delage et al. 2000).

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5) The effect of temperature on the shear strength depends on the drainage condition upon heating and stress history (Graham et al. 2001).

While most of the earlier research works were devoted to study the thermo-mechanical behavior of stiff saturated clays. Only a few research works were devoted to study the thermo-mechanical behavior of natural soft deposits. The aim of this research is to study the thermo-mechanical behavior of natural soft Bangkok clay under temperatures up to 90°C. Intensive laboratory test program using modified oedometer apparatus was conducted. The proposed experimental program covered the effect of temperature on the thermally induced volume change at different stress condition, the induced overconsolidation behavior after heating/cooling cycle for normally consolidated clays at different stress and temperature condition, evolution of the preconsolidation pressure with temperature, and the effect of temperature on the hydraulic conductivity. The following sections present the material and methods of testing along with the testing results and discussions.

MATERIAL

The natural soft clay used in this study was extracted from a depth of 3.0 to 4.0 m of the soft clay layer in the campus of Asian Institute of Technology (AIT) which is within the Central Plain of Thailand. The Central Plain of Thailand contains the deltaic-marine deposit of soft clay layer widely known as "soft Bangkok clay".

Table 1 shows the properties of soft Bangkok clay. The mineralogical composition of Bangkok Clay was investigated by Ohtsubo et al. (2000) using XRD tests. The results show that Bangkok Clay possessed smectite, kaolinite and mica. The major clay mineral is a group of smectite (Montmorillonite and Illite) with range of 54 to 71%, followed by Kaolinite (28-36%) and Mica.

TEST APPARATUS

Figure 1 shows a modified oedometer that can test soil specimen at elevated temperature up to 90°C was used in this study. The modified oedometer consists of conventional oedometer apparatus, ring heater of 600 W capacity, type K thermocouple, water tank, and thermo-controller unit with accuracy 0.1°C. The ring heater was attached to the outer ring of the conventional oedometer apparatus.

Heating of the soil specimen was achieved indirectly by heating the water in the annular space between the outer ring of oedometer and the specimen ring. Using the ring heater, the homogeneity of water temperature around the soil specimen during the test period was insured. The water lost by evaporation from the oedometer unit was simultaneously compensated by hot water supply at the test temperature. The ring heater was connected to the thermo-controller unit to keep the temperature constant within the range of ± 0.1°C.

Table 1 Properties of soft Bangkok clay

Properties	Characteristics value
Liquid limit, LL, (%)	103
Plasticity index, PI, (%)	60
Water content, w (%)	90-95
Liquidity index, LI	0.62
Grain size distribution	
Clay (%)	69
Silt (%)	28
Sand (%)	3
Total unit weight, γ_t, (kN/m^3)	14.3
Dry unit weight, γ_d, (kN/m^3)	7.73
Specific gravity	2.68
Initial void ratio, e	2.4
Color	Dark gray
Activity	0.87
Sensitivity	7.4

Temperature measurements and the feedback signal for the thermo-controller unit were obtained by thermocouple placed in the oedometer annulus space in order to avoid specimen disturbance during the thermocouple intrusion into the specimen. The thermal deformation of the test apparatus were calibrated carefully. The vertical deformation of the oedometer elements were tested by conducting number of tests, without specimen, at different temperatures and stress levels. The radial deformation of the oedometer ring was measured directly after subjecting it for long time in oven at the tested temperature. The measurements show that the effect of the radial deformation is insignificant and can be neglected. Similar conclusion was reported by Towhata et al. (1993). The difference between the specimen temperature and the temperature of water in the annular space was also calibrated by measuring simultaneously the temperature of thermocouple embedded in the specimen center and another one in the annular space.

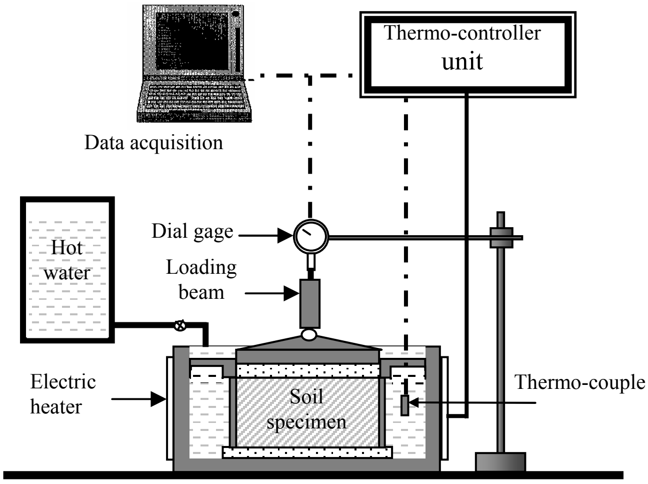


Fig. 1 Schematic drawing for the modified oedometer apparatus

EXPERIMENTAL PROGRAM

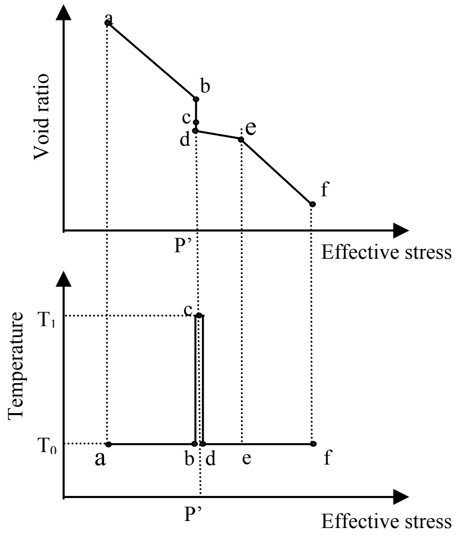
To study the thermo-mechanical behavior of soft Bangkok clay two types of temperature-loading paths were adopted. The first path, called thermal loading path, involved changing the soil temperature at constant stress condition (either, at normally consolidated state or overconsolidated state) to obtain the soil response as a function of temperature (Fig. 2). This path was applied to investigate the thermally induced volume change at different temperatures and stress conditions. To investigate the effect of the stress level on the thermally induced volume change three groups of specimens (each group consists of six specimens) were tested. The specimens of each group were consolidated under different stress levels greater than its natural preconsolidation pressure. Based on the results of the incremental mechanical consolidation test the natural preconsolidation pressure was found to be 70 kPa. The specimens in the three groups were consolidated under 100, 200, 300 kPa respectively. To investigate the effect of the stress history on the thermally induced volume change three specimen of each group were unloaded to different overconsolidation ratios (2, 4, and 8). Then overconsolidated specimen in each group was subjected to heating/cooling cycle (25-90-25^{o}C) while the three normally consolidated specimens were also subjected to different heating/cooling cycle (25-50-25^{o}C, 25-70-25^{o}C, and 25-90-25^{o}C). The amounts of settlements were observed during the heating and cooling phases. The irreversible thermally induced volume change can be calculated at the end of the cooling phase. At the end of the drained heating/cooling phase, the normally consolidated specimens were subjected to incremental mechanical reloading at ambient temperature to obtain the change in the elastic range after subjecting it to different values of thermal load cycle.

The second path, called isothermal mechanical loading path, involved applying mechanical load to overconsolidated clay specimen at elevated temperature (more than the ambient temperature) to investigate the thermal evolution of the soil consolidation curve (Fig.3). This study brings out the effect of temperature on the size of the elastic domain. Further, the effect of temperature on the consolidation rate upon loading can be utilized to estimate indirectly the effect of temperature on the coefficient of hydraulic conductivity. To investigate the effect of the initial preconsolidation pressure (at ambient temperature) on the evolution of the preconsolidation pressure under elevated temperatures two groups of specimen were tested under this path with each group consisted of four specimens. The first group of specimens was consolidated under 100 kPa while the second group of specimens was consolidated under 200 kPa. Both group specimens were subjected to mechanical unloading until OCR=12 at ambient temperature after the consolidation stage. Three specimens of each group were subjected to incremental heat up to different temperature levels (50, 70, 90^{o}C) while the temperature of the latter group of specimens was kept at the ambient temperature (25^{o}C). At the end of the heating stage, the four specimens were subjected to mechanical incremental reloading. The tests were terminated when the specimens were straining continuously indicating the yielding mode and the available points in the effective stress-strain spaces are enough to determine the slope of the compression hardening line.

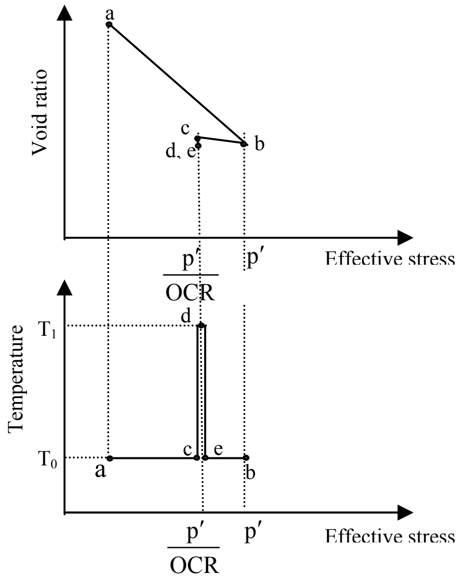
DISCUSSIONS OF THE TEST RESULTS

Thermally Induced Volume Change

The thermally induced volume change after cycles of drained heating/cooling at different stress history was studied by many researchers (e.g. Plum and Esrig 1969; Demars and Charles 1981; Baldi et al. 1988; Towhata et al. 1993; Robinet et al. 1996; Burghignoli et al. 2000; Laloui and Cekerevac 2003).



a) Normally consolidated specimen



b) Over-consolidated specimen

Fig. 2 Thermal loading path

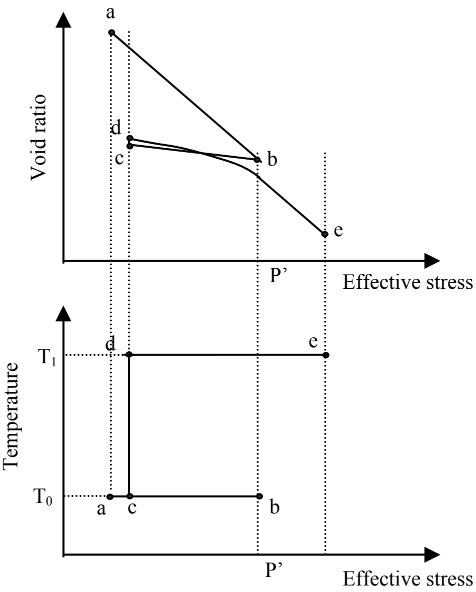


Fig. 3 Isothermal mechanical loading path

It was demonstrated that the normally consolidated clays contract irreversibly and non-linearly upon heating. However, when overconsolidated clays were heated, the magnitude of volume contraction was smaller than that of normally consolidated samples. In addition, the highly overconsolidated clay exhibited reversible volume expansion when heated.

The soft Bangkok clay shows similar thermally induced volume change behavior under heating up to 90°C as shown in Fig. 4. The normally consolidated specimens show irreversible contraction while for the highly overconsolidated specimen (OCR=8) the thermal behavior becomes reversible with initial expansion. Figure 5 shows that the thermally induced volumetric strain at different temperature level depends on the OCR values. At certain temperature level, as the soil condition changed from the normally consolidated state to the overconsolidated state the contraction volumetric strain decreases and becomes expansion beyond certain OCR values.

Robinet et al (1996) attributed the thermally induced volume change behavior to the physico-chemical interactions which are stress independent but dependent essentially on the clay lattice constitution, the chemical nature of the interstitial fluid, and interlayer distance. The soil plasticity index can be considered as an indication for the intensity of the physico-chemical interactions upon heating and may affect quantitatively the thermally induced volumetric strain. Demars and Charles (1982) measured the thermally induced volume change for six different natural marine clays and concluded that the thermally induced volume change increases as the soil plasticity increases. Figure 6 shows the thermally induced volume change results versus the soil plasticity index of different types of normally consolidated clays existing in the literature that were subjected to temperature change of ΔT = 65 to 70°C. A relation between the thermally induced volumetric strain and the soil plasticity index could be deduced. However, it is thought that the soil plasticity index is not the only factor that controls the thermo-mechanical behavior. The percentage of fines can also affect the soil behavior at constant soil plasticity index.

Towhata et al. (1993) studied the effect of the stress level on the thermally induced void ratio change of the normally consolidated clays. It was found that when the normally consolidated clays are subjected to drained heating the amount of void ratio change is independent on the stress level (preconsolidation pressure). The experimental program of the current research work, investigated the effect of the preconsolidation stress on the void ratio change for the normally and the overconsolidated clay specimens. Figure 7 shows the thermal void ratio change on clay specimens consolidated under different stress values (100, 200, 300 kPa) and unloaded to different stress histories (OCR = 1, 2, 4, 8) before subjecting to temperature change $\Delta T = 65^{o}C$. The results indicate that the void ratio changes are independent on the initial preconsolidation pressures.

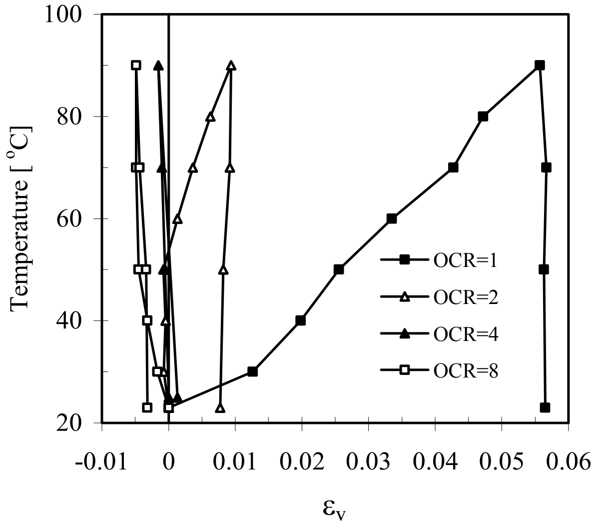


Fig. 4 Soft Bangkok clay thermal volumetric strain during drained heating/cooling cycle at different OCR values (preconsolidation pressure = 200 kPa)

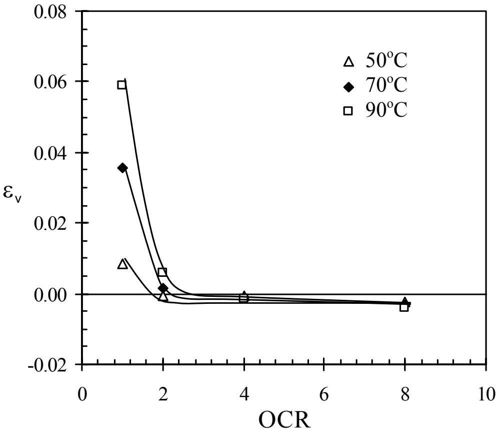


Fig. 5 Effect of OCR values on the thermally induced volumetric strain of soft Bangkok clay at different temperature level (preconsolidation pressure = 100 kPa)

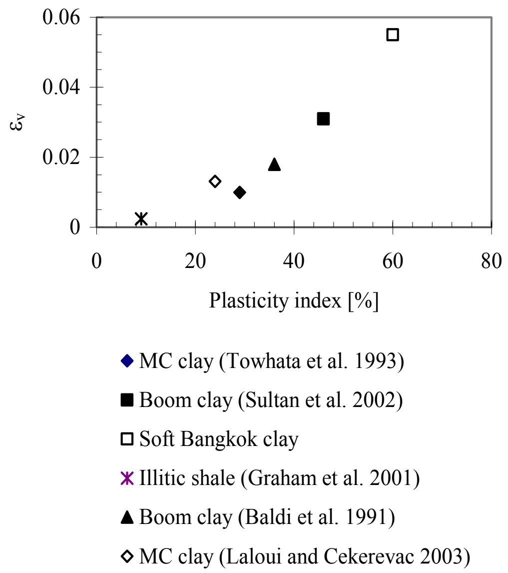


Fig. 6 Effect of soil plasticity index on the thermally induce volumetric strain for different normally consolidated clays ($\Delta T = 65^{o}C$)

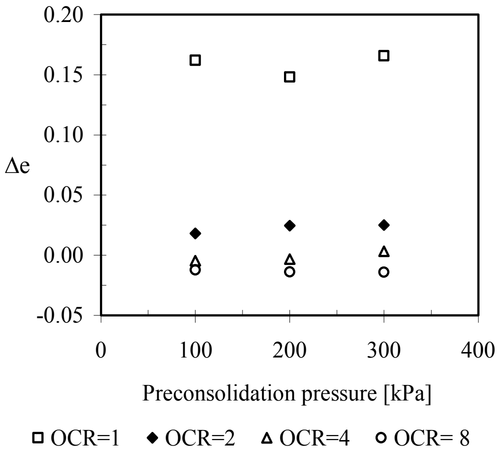


Fig. 7 Effect of the preconsolidation pressure on the soft Bangkok clay thermally induce void ratio change at different OCR values ($\Delta T = 65^{o}C$, $T_o = 25^{o}C$)

Evolution of the Preconsolidation Pressure with Temperature

Many experimental research works (e.g. Tidförs and Sällfors 1989; Eriksson 1989; Moritz 1995; Boudali et al. 1994, Leroueil, and Marques 1996; Leroueil 1997; Sultan et al. 2002; Cekerevac et al. 2002) have been carried out to study the effect of temperature rise on the consolidation behavior for different types of soils. It was found that as the soil temperature increases the preconsolidation pressure decreases. Figure 8 shows the evolution of the preconsolidation pressure normalized by the preconsolidation pressure at T= 20°C of different soil types in literature. The behaviour of soft Bangkok clay shows similar trend. Figure 9 shows the thermal evolution of preconsolidation pressure of soft Bangkok clay at two different preconsolidation pressures (100, and 200 kPa).

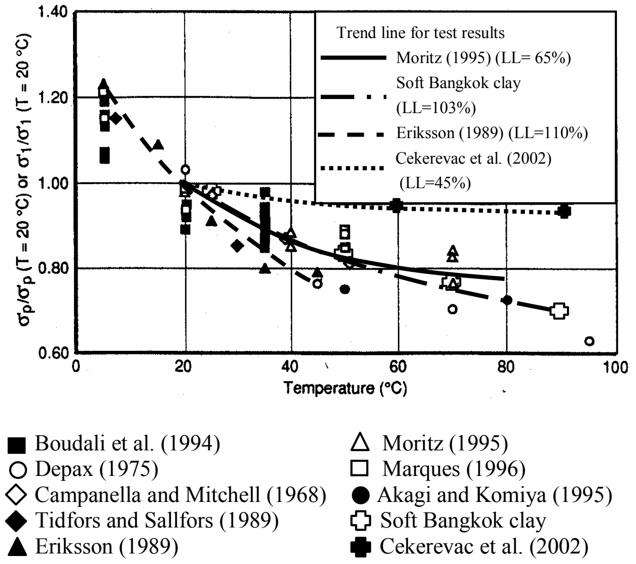


Fig. 8 Variation of the normalized preconsolidation pressure with temperature (after Leroueil and Marques, 1996).

The experimental results show the percentage of the change in preconsolidation pressure is stress level independent. At T = 90°C, the preconsolidation pressure change was 24 and 22 % for 100 and 200 kPa preconsolidation pressures, respectively.

Different equations have been proposed in the literature to model the thermal evolution of the preconsolidation pressure. Boudali et al. (1994) assume linear relation equation between the preconsolidation pressure and temperature. Nonlinear relation has been proposed by Moritz (1995) and Cekerevac et al. (2002) as given in Eq.1 and Eq. 2, respectively.

$$\frac{\sigma'_c(T)}{\sigma'_c(T_0)} = \left[\frac{T_0}{T}\right]^{\alpha} \qquad (1)$$

$$\frac{\sigma'_c(T)}{\sigma'_c(T_0)} = 1 - \gamma\left[\log\left(\frac{T}{T_0}\right)\right] \qquad (2)$$

where $\sigma'_c(T_0)$ and $\sigma'_c(T)$ are the preconsolidation pressures at room and tested temperature, respectively, α and γ are the model parameters which depend on the soil type. Soft Bangkok can fit well with the two equations at model parameter α=0.16 for Eq. 1 and γ=0.42 for Eq. 2 as shown in Fig. 10a, b.

Figure 11 shows the thermal evolution of the preconsolidation pressure normalized by the preconsolidation pressure at T= 20°C predicted by Eq. 2 at different values of parameter γ. The predicted results indicate that the parameter γ can express the intensity of the preconsolidation pressure changes with temperature. As γ increases, the change in the preconsolidation pressure due to temperature increases. Cekerevac et al. (2002) proposed that the model parameter γ could be related to the soil liquid limit varying from 45 to 110% as shown in Fig. 12. The trend lines of the test results in Fig. 8 show that the soils that have higher liquid limit values demonstrate higher thermal evolution of the preconsolidation pressure and consequently corresponding to high γ values. Soft Bangkok clay which has liquid limit about 103% shows that the proposed relationship can be applicable (Fig. 12).

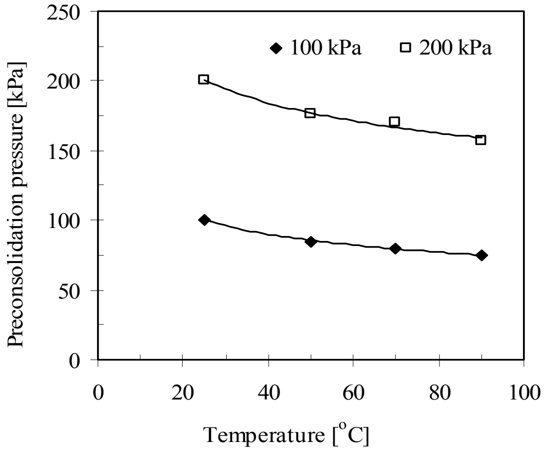


Fig. 9 Thermal evolution of soft Bangkok clay preconsolidation pressure

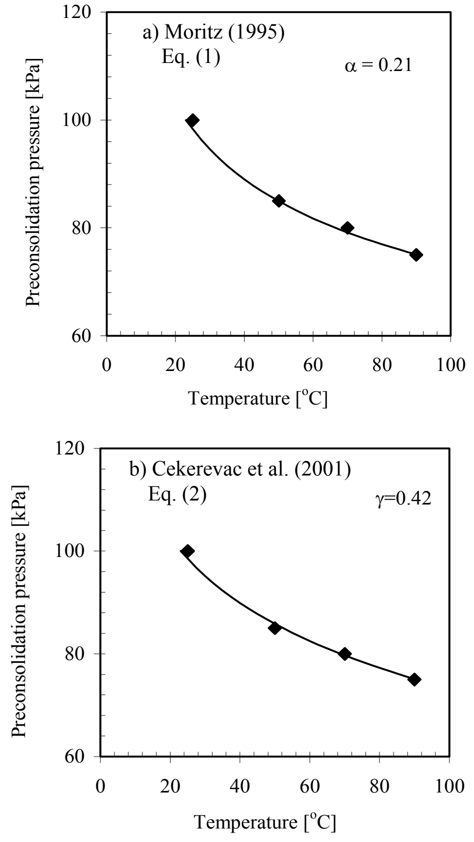


Fig. 10 Comparison between measured and predicted soft Bangkok clay thermal evolution of the preconsolidation pressure

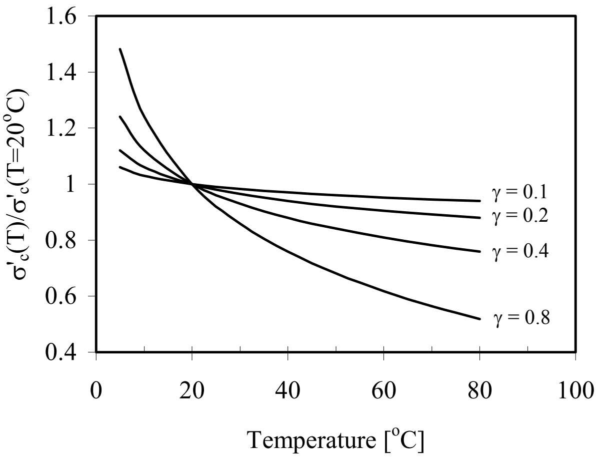


Fig. 11 Thermal evolution of preconsolidation pressure at different values of γ

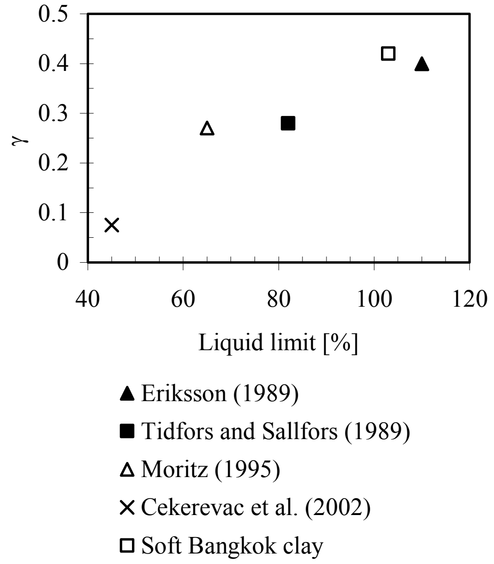


Fig. 12 Evolution of the parameter γ as function of soil liquid limit (after Cekerevac et al. 2002)

Thermally Induced Overconsolidation Behavior

Towhata et al. (1993), Robinet et al. (1996), and Burghignoli et al. (2000) found that when the normally consolidated clays are subjected to drained heating/cooling cycle, an increment of stress is required to reach the yielding limit again. Within this stress increment the soil shows high compression stiffness (elastic behavior) when it is reloaded. This means that heating/cooling cycle increases the elastic range and induces overconsolidation behavior. Figure 13 shows the thermally induced overconsolidation behavior for soft Bangkok clay specimen consolidated under 100 kPa before subjecting to drained heating and cooling cycle (25-90-25°C).

The current testing program also investigated the effect of temperature and the initial ambient preconsolidation pressure on the amount of increase in the elastic range after subjecting to drained heating/cooling cycle. Normally consolidated clay specimens at different preconsolidation pressures (100, 200, 300 kPa) were subjected to different temperature levels (50, 70, 90°C). The experimental results are plotted in Fig 14. The experimental results show that as the temperature of the drained heating/cooling cycle increases, the preconsolidation value increases. Moreover, the results also show that at constant temperature level the percentage of preconsolidation pressure change after drained heating/cooling cycle is independent of stress level. The change in the preconsolidation value upon subjecting to drained heating/cooling cycle (25-90-25°C) for the clay specimen consolidated under 100 kPa, was 35 kPa while for the clay specimen consolidated under 200 and 300 kPa, it was 75 and 105 kPa, respectively.

The test results have been normalized as shown in Fig. 15 using the initial ambient temperature preconsolidation pressure, $\sigma'_c(T_0)$. The increase in the preconsolidation pressure after subjecting to drained heating/cooling cycle was reduced to a single linear relationship between the maximum cyclic temperature and the normalized preconsolidation pressure.

Effect of Temperature on the Hydraulic Permeability

The effect of heat on the coefficient of the hydraulic conductivity has been investigated experimentally by many researchers. Some of them (e.g. Habibagahi 1977 and Towhata et al. 1993) used the indirect method which employs the measurements of the coefficient of consolidation, c_v , and the coefficient of volume change, m_v, that obtained from isothermal consolidation tests performed at various temperatures level. Other investigators (e.g. Morin and Silva 1984 and Delage et al. 2000) used the direct method, the constant head method. All of the researchers reported that the hydraulic conductivity of soil increases with increasing the temperature.

There are three factors affecting the soil hydraulic conductivity. First, the properties of the fluid (soil liquid phase) which includes the viscosity and the unit weight of the fluid. Second, properties of soil matrix which describe the size of flow channel between soil particles within the soil sample. Third, the physico-chemical interactions between soil particles and the surrounding liquid which affect also the size of the flow channel. Water can be bound to the soil matrix. The degree of binding varies from unbounded or free water which is at distance from the soil particle surface and can flow under normal hydraulic gradient, to strongly bound or adsorbed water, called diffuse double layer, which is near the soil particle surface. Therefore, the change in hydraulic conductivity can be attributed to either the changes in diffuse double layer thickness, the soil matrix as a result of soil volume changes, or the fluid properties.

Morin and Silva (1984), Mitchell (1993) and Delage et al. (2000) found that the effect of temperature on the thickness of the diffuse double layer and the soil matrix is insignificant. The effect of thermally induced volume change on the soil matrix is small to be responsible for the hydraulic conductivity change at elevated temperature (Houston and Lin, 1987).

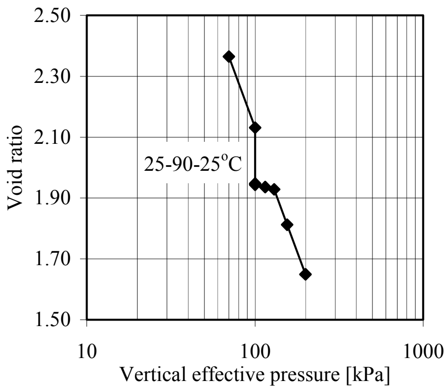


Fig. 13 Overconsolidation behavior of normally consolidated soft Bangkok clay after heating/cooling cycle

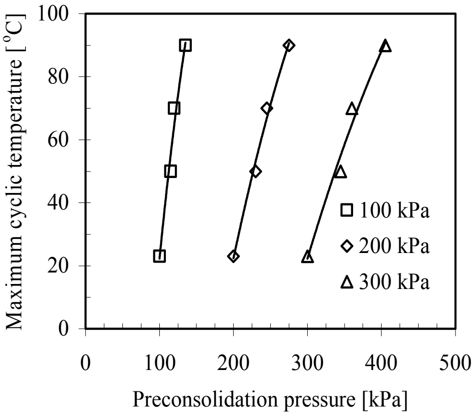


Fig. 14 The change in the preconsolidation pressure of the normally consolidated soft Bangkok clay at different stress level after heating/cooling cycle at different temperature level

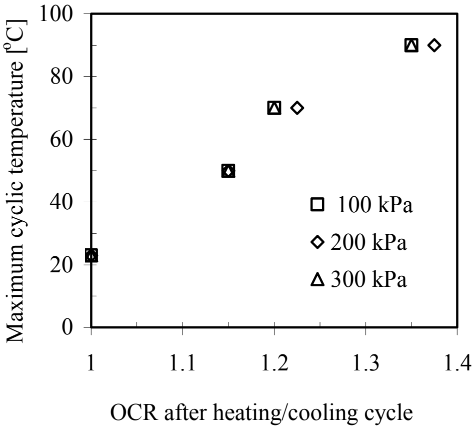


Fig. 15 The change in the OCR value of the normally consolidated soft Bangkok clay after heating/cooling at different temperature level

On the other hand, the temperature has direct significant effect on the physical properties of the soil liquid especially the viscosity. Therefore, at certain soil porosity the ratio between the hydraulic permeability at tested temperature k (T) and at ambient temperature k (T_o) can be estimated using Kozeny-Carman equation as follows:

$$\frac{k(T)}{k(T_o)} = \frac{\mu(T_o)\gamma_w(T)}{\mu(T)\gamma_w(T_o)} \tag{3}$$

where $\mu(T)$ and $\mu(T_o)$ are the pore water viscosity at test and room temperature, respectively, and $\gamma_w(T)$ and $\gamma_w(T_o)$ are the pore water unit weight at test and room temperature, respectively. The thermal variation of free pure water viscosity can be estimated according to Hillel (1980) as follows:

$$\mu(T) = -\,0.00046575 \ln(T) + 0.00239138 \tag{4}$$

where T is the water temperature. Hence, Eqs. 3 and 4 can be used to predict the temperature effect on the hydraulic conductivity.

Although, the mentioned disadvantages by Tavenas et al. (1983) and Delage et al. (2000) for the determination of soil permeability using the indirect method, it can be used for comparison purpose between the soil permeability at different temperatures because of the cancellation of the error source. Based on direct method experimental results, Delage et al. (2000) found that at different temperature levels the measured coefficient of volume change values, m_v, are 3 to 4 times higher than the calculated m_v using the following equation:

$$k = m_v \gamma_w c_v \tag{5}$$

Therefore, it was concluded that the indirect permeability measurement from the consolidation test yielded higher value. However, the error source in the indirect method is temperature independent. The results of the iso-thermal oedometric experimental program at different temperature level have been used to determine indirectly the hydraulic permeability of soft Bangkok clay at different temperature. Figure 16 shows the increase in the consolidation rate of soft Bangkok clay as the test temperature increases. Furthermore, Fig. 17 shows the increase in the measured hydraulic permeability of soft Bangkok clay normalized by the ambient temperature hydraulic conductivity value. The predicted increase in the hydraulic permeabilities using Eq. 3 and 4 has been plotted also in Fig. 17 for comparison purposes.

The experimental results show that the increase in permeability due to temperature increase is close to the predicted values using Eqs.3 and 4. The observed deviation of the experimental results from the predicted values can be attributed to the variation of salt concentration in water which significantly modifies the relationship between viscosity of water and temperature (Burghignoli et al. 1995).

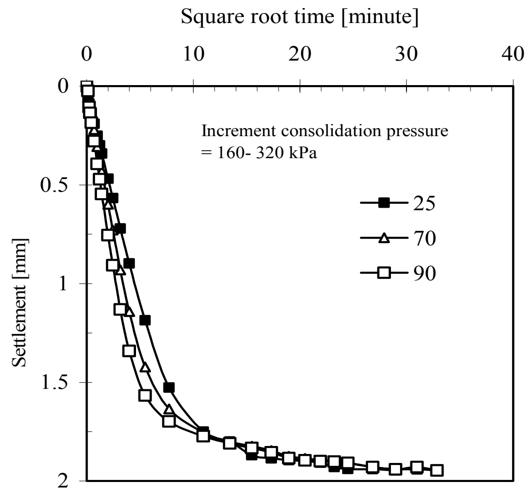


Fig. 16 Consolidation rate of normally consolidated soft Bangkok clay at different temperature

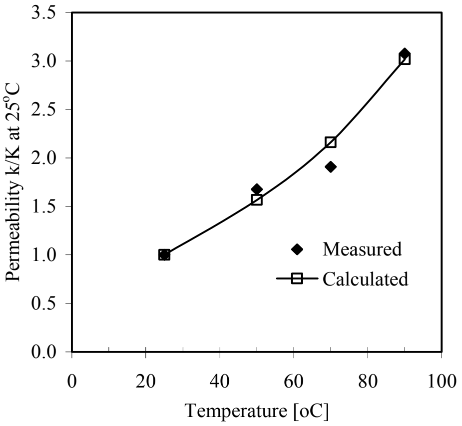


Fig. 17 Comparison between the measured and the calculated variation in the hydraulic permeability with temperature

CONCLUSIONS

The results of the experimental program carried out on the soft Bangkok clay to investigate the thermo-mechanical behavior of the soft deposits can be concluded in the following points:

1) Thermally induced volume change is stress history dependent and stress level independent.
2) The thermal evolution of the preconsolidation pressure is nonlinear and the percentage of the evolution is stress level independent.
3) The normally consolidated specimen shows overconsolidation behavior after subjecting to drained heating/cooling cycle. This behaviour is function of the cyclic temperature.
4) The hydraulic permeability of saturated soils increases as the test temperature increases. This increase is mainly due to the corresponding decrease in the soil liquid viscosity with temperature.
5) The thermo-mechanical behaviour of saturated fine-grained soils, under temperature less than the pore liquid boiling point, has been attributed to the physico-chemical changes, soil plasticity and percentage of fines. Together, these aforementioned factors can be considered as indication for the intensity of the thermally induced changes.

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