## TEMPERATURE EFFECTS ON UNDRAINED SHEAR CHARACTERISTICS OF CLAY

PISIT KUNTIWATTANAKUL<sup>i)</sup>, IKUO TOWHATA<sup>ii)</sup>, KANTA OHISHI<sup>iii)</sup> and ICHIRO SEKO<sup>iv)</sup>

## ABSTRACT

This paper presents results of a study on the effects of high temperature (up to  $90^{\circ}$ C) on undrained shear characteristics of clay in both normally consolidated (NC) and overconsolidated (OC) states. The study is based on isotropically consolidated undrained triaxial tests carried out using a temperature controlled triaxial apparatus. Several sequences of heating and consolidation were used to gain insight into the effects of temperature on clay. The study reveals that: (1) in NC state, both the initial secant modulus and the shear strength increase with increasing temperature, and (2) in OC state, only the initial secant modulus increases with a temperature rise, but the shear strength is not affected by heating. This paper further explains these experiment results in terms of micro-resistance and macro-resistance of the clay structure.

Key words: <u>clay</u>, <u>consolidated undrained shear</u>, heat, shear strength, <u>stress-strain curve</u>, <u>temperature effect</u> (IGC: D6/D8)

## **INTRODUCTION**

In the near future, effects of high temperature on soil behavior will be one of the most important aspects in geotechnical engineering. The growing demand, but limited supply, of energy and mineral resources has created a need to use more and more complex facilities for the extraction and management of these resources. It has been predicted that some of these facilities, for example: nuclear waste disposal (Poorooshasb and James, 1989; Radhakrishna et al., 1989) and heat storage (Bergenstahl et al., 1994), are going to cause significant changes in the temperature of soil surrounding them. The change of temperature, in some cases, is going to be so severe that the existing geotechnical engineering experience may not be sufficient to handle it with certainty. As a result, increasing attention is being given to the study of temperature effects in recent years.

Temperature effects on strength and stress-strain characteristics of clay have been a subject of controversy for more than 20 years. Conflicting experimental results have always been obtained in studies conducted in this area. On the one hand, there were many experimental results which strongly asserted that an increase in temperature caused weakening in clay, and on the other hand, there were also many test results which clearly indicated that an increase in temperature strengthened clay. Some researchers have tried to explain their results using theories existing in the current literature. It seems, however, that the current state of the art cannot fully explain the results of the studies.

Several investigators have found that an increase in temperature caused weakening in clay, for instance, Mitchell (1964), Murayama (1969), Sherif and Burrous (1969), Hueckel and Baldi (1990). Mitchell found that higher temperature caused lower shear strength and higher pore pressure build-up during shear; his study was conducted on compacted San Francisco Bay mud by carrying out undrained triaxial tests. Murayama reported that an increase in temperature reduced the elastic modulus of Osaka Clay specimens in unconfined compression tests. Sherif and Burrous showed that higher temperature caused reduction in unconfined compressive strength of kaolin clay. Hueckel and Baldi demonstrated that an increase in temperature induced lower shear strength, lower stiffness, and higher volume change during shear; their study was based on drained triaxial tests carried out on overconsolidated Pontida silty clay. It should be noted that the methods of heating used by Mitchell and Hueckel and Baldi were different from those used by

<sup>&</sup>lt;sup>i)</sup> Engineer, Fudo Construction Co., Ltd., Tokyo.

<sup>&</sup>lt;sup>ii)</sup> Professor, the University of Tokyo.

iii) Graduate Student, ditto.

<sup>&</sup>lt;sup>iv)</sup> Engineer, Chuo Kaihatsu Co., Ltd., Tokyo.

Manuscript was received for review on August 30, 1993.

Written discussions on this paper should be submitted before October 1, 1995 to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4 F, Kanda Awaji-Cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

Murayama and Sherif and Burrous. The former employed drained heating (heating carried out while the drainage valves are opened), whereas the latter used undrained heating (heating with the drainage valves closed).

Many studies, on the other hand, revealed that an increase in temperature strengthened clay: for example, Laguros (1969), and Houston et al. (1985). Laguros showed that unconfined compressive strength of three clays increased with increasing temperature: the plasticity index,  $I_P$ , of the clays varied from 29% to 47%. However, he found for illitic soil that the strength increased with increasing temperature up to 22.2°C; after that, it decreased with increasing temperature. It should be noted that Laguros' test specimens were compacted at the shear temperatures. Houston et al. found that shear strength of both illite and smectite-rich clay increased with increasing temperature. Their study was carried out using undrained triaxial tests with drained heating.

In addition, there is evidence indicating that specimens prepared under higher temperature have higher strength (e.g. Noble and Demirel, 1969; Tsuchida, 1990). Noble and Demirel presented the results of direct shear tests on Iowa clay (liquid limit,  $w_L$ , =89% and  $I_P$ =59%) that showed the effects of both temperature at consolidation and temperature at shear. Their results clearly indicated that the higher the consolidation temperature the greater the shear strength at any given shear temperature. For a given consolidation temperature, however, the shear strength decreased with increasing shear temperature. Tsuchida showed that shear strength and stiffness of specimens trimmed from clay cakes preheated during reconstitution were higher than those without preheating. In addition, the stress-strain curves of the preheated specimens were similar to those of undisturbed samples.

In view of the apparent lack of agreement among the previous studies and because of the increased use of clay in high temperature environments, it was decided to further enrich the existing body of knowledge in this area by performing an additional study at the University of Tokyo. The study covered the effects of temperature on: (1) volume change behavior, (2) permeability, and (3) stress-strain characteristics. The results of the study on volume change behavior and permeability have already been published by Towhata et al. (1993). This paper, therefore, deals only with the study of stress-strain characteristics in which the effects of heating (up to 90°C) on undrained shear behavior of both normally consolidated (NC) and overconsolidated (OC) clays were studied extensively. In this paper, an explanation of the temperature effects on stress-strain characteristics from a microstructure point of view is presented, and one of the reasons for disagreement among the previous studies is also pointed out. In addition, before presenting the results of the study on stress-strain characteristics, general knowledge about temperature effects on volume change and pore pressure which is deemed to be essential for the subsequent discussions is summarized.

## **OVERVIEW OF TEMPERATURE INDUCED VOLUME CHANGE AND PORE PRESSURE IN CLAY**

An extensive study of the mechanism of temperature effects on volume change and pore pressure of clay was carried out by Campanella and Mitchell (1968). According to this study, an increase in temperature affects clay mainly in three ways: (1) it causes expansion of water in clay pores, (2) it induces expansion of clay particles, and (3) it activates rearrangement of the clay particles. The response of clay to these changes depends on the drainage conditions of the clay mass. If the drainage takes place fully (drained heating), then the volume change is governed by the expansion of clay particles and the particle rearrangement since the expanding water is free to leave the clay mass. On the other hand, if the drainage is not allowed (undrained heating), then the expansion of water induces a change in the pore pressure and causes an overall volume expansion.

In drained heating, Towhata et al. (1993) demonstrated that the volume change depends on the stress histories of the clay. For NC clay or reloaded OC clay, heating from 20°C to 90°C causes void ratio reduction ranging from 0.01 to 0.015. Unloaded OC clay, except lightly OC clay, exhibits an increase in void ratio upon heating from  $20^{\circ}$ C to  $90^{\circ}$ C. The magnitude of the increase in void ratio depends on the OCR: the increase in void ratio varies from 0.005 for an OCR of 3.5 to 0.01 for an OCR of 56.

In undrained heating, since the expansion of water in the clay pores is much larger than the expansion of soil particles (Campanella and Mitchell, 1968; Baldi et al., 1988), undrained heating naturally causes an increase in void ratio. In addition, the expansion of water also induces an increase in pore pressure in both NC and OC clays. It should be noted that even though the soil skeleton of unloaded OC clay tends to expand upon heating, undrained heating causes an increase in pore pressure since the expansion of the pore water is much larger than the increase in volume of the soil skeleton.

## MATERIAL, EQUIPMENT, AND TESTING

This study was performed on reconstituted clay consolidated from a slurry prepared by mixing clay powder with distilled water. The powder is commercially available kaolin powder sold under the classification of MC. Mineral composition analysis by X-ray diffraction showed that this kaolin contained considerable quantities of other minerals mainly of the mica and quartz groups (Ampadu, 1991). The liquid limit and the plasticity index of the clay are 70% and 29% respectively.

Specimens used in this study were trimmed from clay cakes which were one-dimensionally preconsolidated from the slurry in a consolidation tank under a vertical pressure of 98 kPa. The slurry was prepared at a water content of 160%. Prior to the consolidation, the slurry was kept under vacuum for a minimum of 2 days to minimize air entrapped during the mixing process.

This study was carried out using a temperature controlled triaxial apparatus as shown in Fig. 1. The apparatus consists of two cells; namely inner and outer cells. The inner cell was filled with water whose temperature was controlled by a variable power heater submerged directly in the water. The amount of power supplied to the heater was automatically adjusted by a controller unit (not shown here) in order to balance the amount of heat transferred from the cell to the surrounding environment. This method of temperature control allowed the temperature to be maintained with an accuracy of  $\pm$ 0.1°C. The chamber between the inner and the outer cells was filled with air. The air was employed: (1) as a medium to transfer pressure from a pressure control unit to the water in the inner cell, and (2) as an insulator to minimize the heat transferred from the inner cell. In addition, to further minimize the heat transfer, the base of the inner cell was insulated by a plastic disc whose thermal conductivity and heat capacity were 0.2 Kcal/m.hr.°C and 0.4 cal/°Cg respectively.

All the tests were isotropically consolidated undrained triaxial compression tests in which the cell pressure was kept constant during shear. The tests were carried out using specimens 5 cm in diameter and 10 cm in height. The specimens were wrapped with filter-paper side-drains to accelerate both drainage during consolidation and excess pore water pressure equalization during shear. Lubricated sheets were put at both ends of the specimen to reduce stress and strain non-uniformity in the specimens. The shearing was done in a strain controlled apparatus with a



Fig. 1. Temperature controlled triaxial apparatus

strain rate of about 5% per hour.

Details of the materials, equipment, and testing methods can be found in Kuntiwattanakul (1991).

In order to gain insight into the temperature effects, several consolidation and heating paths were used as probes. Four sets of NC specimens and three sets of OC specimens were prepared under different consolidation and heating paths. Hereinafter, these paths will be named Path 1 through Path 4 for NC specimens and Path 5 through Path 7 for OC specimens.

Since the time required for specimen preparation for each consolidation and heating path is slightly different, the effects of time differences should be understood in order to properly evaluate the temperature effects. Therefore, the time effects were also briefly investigated in this study.

## TIME EFFECTS

The study of time effects was carried out at room temperature as follows. Specimens were consolidated under a pressure of 196 kPa. The pressure of each specimen was maintained for different periods of time ranging from about 3 hours to 6 days (It should be noted that the primary consolidation, as determined by conventional elog t plot method, was complete within about two hours). Thereafter, all the specimens were sheared under undrained conditions.



Fig. 2. Dependency of secant modulus on consolidation period



Fig. 3. Dependency of maximum deviator stress on consolidation period

## KUNTIWATTANAKUL ET AL.

Dependencies of the initial secant modulus (at 0.1% shear strain) and the maximum deviator stress on the consolidation periods derived from the results obtained by

the above procedure are presented in Figs. 2 and 3 respectively. Figure 2 clearly shows that the longer the consolidation period the higher the modulus; when the consoli-



Fig. 4. Diagrams showing consolidation and heating paths for NC clay

dation period was increased from 3 hours to 6 days, the modulus increased about 35%. In contrast, Fig. 3 shows that the maximum deviator stress is not significantly affected by the consolidation period. This suggests that the structure of the clay gradually changes with time to produce a new structure which is more effective in resisting the subsequent shear distortion. This new structure, however, is gradually destroyed in the course of the shearing process as manifested through the independence of the shear strength on the consolidation time.

It should be noted that, in the study of temperature effects, the final consolidation pressure for each specimen was maintained overnight (about 16 to 18 hours). Thereafter, the specimens were heated using different heating paths in which heating times were slightly different (3 to 5 hours). The study of time effects revealed that these slight differences in testing times were unlikely to have any significant effect on the behavior of the specimens. The differences in the modulus caused by such time differences would be, according to Fig. 2, less than 3%.

## TEMPERATURE EFFECTS ON NORMALLY CONSOLIDATED CLAY

Procedures for carrying out this investigation were as follows. Specimens were first consolidated in the triaxial cell under one of the four paths of consolidation and heating. Thereafter, the specimens were sheared in an undrained manner. Each consolidation and heating path is illustrated by diagrams in Fig. 4; this diagram will be hereafter called the history diagram. Each diagram consists of two curves, the void ratio versus effective mean pressure (e-p') curve and the temperature versus pressure (T-p') curve. The following sections describe the details of each case together with shear test results.

In the following sections, the results of each triaxial test will be presented using four figures designated **a**, **b**, **c**, and **d** as shown in Figs. 5 and 7 to 9. Figs. **a** and **b** show diagrams of deviator stress,  $q = (\sigma_1' - \sigma_3')$ , plotted against axial strain,  $\varepsilon_a$ . The former presents the results of the whole range of strain up to failure, while the latter enlarges the portion between 0% and 1% strain. Fig. **c** displays a diagram of the excess pore pressure induced by the shearing process vs. axial strain. It should be noted that the excess pore pressure shown in this diagram does not include the pore pressure caused by the increase in the total mean principal stress due to the increase in the axial stress. Fig. **d** illustrates the stress path, i.e., deviator stress vs. effective mean principal stress,  $p' = (\sigma_1' + 2\sigma_3')/3$ .

#### Path 1

The heating and consolidation sequence of this path is schematically presented in the history diagram in Fig.



Fig. 5. Results of undrained shear test of the specimens prepared under Path 1

4(a). The specimens were consolidated at room temperature under pressures increasing from 20 kPa to 196 kPa, as shown by step 1 to step 2 in the diagram. The specimens were then kept overnight under a pressure of 196 kPa at room temperature (step 2 to 3). During this period, the secondary consolidation took place and the void ratio decreased as shown in the e-p' diagram. Thereafter, the specimens' temperature was raised to 90°C using the drained heating method (step 3 to 4), and the volume of water draining out from the specimens was monitored by a burette. The temperature was maintained until no more significant amount of water drained from the specimens, a process which usually took about 3 hours. It should be kept in mind that the void ratio curve in the diagram is exaggerated for the sake of illustration. Actually, the void ratio changes during overnight consolidation and during heating were both of an order of 0.01 which is equivalent to 0.4% volumetric strain.

The results of the shearing test of this path are presented in Fig. 5 together with the results of the unheated specimens; the unheated specimens were prepared using the same procedure described above with the exception that heating (step 3 to 4) was omitted. This figure clearly shows that: (1) shear strength and stiffness of heated specimens are considerably higher than those of unheated specimens; (2) stress paths of heated specimens lie above those of unheated specimens; and (3) magnitudes of shear-induced pore pressure of heated specimens are lower. These results suggest that the heating process causes a significant increase in shear strength and stiffness of clay.

It should be noted that although heating at  $50^{\circ}$ C and  $70^{\circ}$ C was also carried out in this study, due to the limited publishing space, only the results of specimens heated at  $90^{\circ}$ C are presented here. However, the results of the specimens heated at  $50^{\circ}$ C and  $70^{\circ}$ C show that the changes brought about by heating are gradual (Kuntiwattanakul, 1991).







Fig. 7. Results of undrained shear test of the specimens prepared under Path 2

#### Path 2

The history diagram of Path 2 is presented in Fig. 4(b). Step 1 through 3 of this case were identical to those of Path 1. However, the heating process of Path 2 was different from that of Path 1. In Path 2, the specimens were first heated in undrained conditions (step 3 to 4); the heating induced pore pressure in the specimens as shown in Fig. 6. After the pore pressure was fully developed, the drainage valves were opened and the pore pressure was allowed to dissipate (step 4 to 5). The total elapsed time for the undrained heating and for the dissipation of pore pressure was about 5 hours.

The shear results for this case are compared with those of unheated and those of Path 1 in Fig. 7. This figure suggests that the stress-strain curves for this case in both strain ranges are essentially the same as those of Path 1. In other words, the strength and stiffness of these two cases are essentially the same. However, the stress paths of Path 2 are slightly lower.

#### Path 3

With reference to the history diagrams in Fig. 4(c), the specimens were initially consolidated at room temperature under pressures increasing from 20 to 137 kPa (step 1 to 2), and the final pressure was maintained overnight (step 2 to 3). Thereafter, the specimens were heated at 90°C under drained conditions for about 3 hours (step 3 to 4). Finally, the consolidation pressure was further in-

creased to 196 kPa (step 4 to 5). The results of the study on volume change behavior using oedometers revealed that the e-log p curves of specimens heated and then consolidated beyond the apparent maximum past pressure are above those of unheated specimens. In other words, at any pressure beyond the apparent maximum past pressure the corresponding void ratio of a heated specimen is larger than that of an unheated one (Towhata et al., 1993).

The results of this case are compared with those of Path 1 in Fig. 8. This figure indicates that the stress-strain curves and, thus, strength and stiffness of Path 3 are comparable to those of Path 1. However, the stress paths of Path 3 lie between those of Path 1 and those of unheated specimens.

### Path 4

In this case, the specimens were heated to  $90^{\circ}$ C and then cooled to room temperature in drained conditions (*see* Fig. 4(d)). The consolidation and heating steps from 1 to 4 were identical to those of Path 1. However, after the heating the specimens were slowly cooled to room temperature (step 4 to 5): with cooling process taking about 20 hours. Although the results of drained heating indicated that heating was completed within 3 hours, it was decided to adopt a longer cooling period to make sure that cooling was carried out under perfect drained conditions. This is because if undrained cooling acciden-



Fig. 8. Results of undrained shear test of the specimens prepared under Path 3



Fig. 9. Results of undrained shear test of the specimens prepared under Path 4

tally occurs in any parts of the specimens, a decrease in pore pressure would occur which would further consolidate the specimens along the NC path in e-log p space beyond the specified pressure of 196 kPa. When the pore pressure returns to the original level, however, the specimens would rebound along the OC path. As a result, there would be a residual decrease in void ratio, and the specimens would become OC. On the other hand in heating, if the pore pressure occurs, it would be positive. As a result, the specimens would rebound along the OC path in e-log p space. When the pore pressure is fully dissipated, specimens would be reconsolidated, more or less, along the same path to the same void ratio. This would cause no significant changes in the specimens.

The results of the shearing of Path 4 are compared with those of Path 1 in Fig. 9. This figure shows that a cycle of heating and cooling also causes a significant increase in the initial stiffness of specimens. The initial part of the stress-strain curves of Path 4 are comparable to those of Path 1. However, the curves gradually divert and join those of the unheated specimens at an axial strain of about 4%. Finally, the strength of the heated and then cooled specimens is found to be equal to that of the unheated specimens. The stress paths of Path 4 are initially located between those of Path 1 and the unheated specimens. The curves gradually join those of the unheated specimens. It should be noted that the results of this path are similar to those reported by Tsuchida et al. (1991).

Since the cooling process took 20 hours, the total consolidation period was about 40 hours. In other words, the consolidation of Path 4 was about 22 hours longer than that of the unheated specimens. If the increase in stiffness of the specimen for this case was mainly due to this longer consolidation period, the magnitude of the increment should have been, according to Fig. 2, only about 6%, however, the magnitude of the increase in stiffness was about 20%.

## **TEMPERATURE EFFECTS ON OVERCONSOLI-DATED CLAY**

Three types of consolidation and heating paths for specimens in OC state (Paths 5, 6, and 7) were investigated. The history diagrams for these paths are shown in Fig. 10. The following sections describe the details of each case together with the shear results.

#### Path 5

The consolidation and heating sequence of this path was as follows (*see* Fig. 10(a)). Specimens were first consolidated at room temperature under a pressure of 196 kPa and then kept overnight (step 1 to 3). (These processes were the same as those for NC specimens). The specimens were then unloaded (step 3 to 4) by increasing the back pressure to produce an OC state with OCR values of 2.2, 4.0, and 8.0. A magnitude of 2.2 was selected because it was equivalent to that of the heat-induced pore pressure caused by undrained heating at  $90^{\circ}$ C (Path 7), and, therefore, their results can be compared later.



Fig. 10. Diagrams showing consolidation and heating paths for OC clay







Fig. 12. Results of undrained shear test of the specimens prepared under Path 5 with OCR=8

KUNTIWATTANAKUL ET AL.

Thereafter, the specimens were heated at  $90^{\circ}$ C under drained conditions (step 4 to 5), and the heating was maintained until no significant amount of water was drained from the specimens. This took about 3 hours. After heating, the specimens were sheared.

The typical results of this case are compared with those of unheated specimens in Figs. 11 and 12 for the OCR of 2.2 and 8 respectively. The unheated specimens were prepared using exactly the same process as the heated specimens except that no heating was applied. It can be noted from these figures that the results of all the OCRs show the same pattern as follows: (1) The maximum deviator stresses of both heated and unheated specimens are virtually the same. This trend is different from that of NC specimens. (2) The initial stiffness of the heated specimens is greater as can be seen in the enlarged stress-strain plots. This result is also observed in the NC state. (3) The stress paths of heated specimens are located to the left of those of unheated specimens, i.e., the shear-induced pore pressures of heated specimens are higher. This behavior is opposite to that of NC specimens.

#### Path 6

With reference to the history diagram in Fig. 10(b), preparation of the specimen for this case was carried out as follows. In step 1 to 4, the specimen was consolidated at 196 kPa, kept overnight, and heated at 90°C under drained conditions using the same procedure as in Path 1. Thereafter, the specimen was unloaded to an OCR of 2.2 by increasing the back pressure (step 4 to 5). Finally, the specimen was sheared.

The results of this case are compared with those of Path 5 and Path 7 in Fig. 13. Discussion of these results will be made following the details of Path 7.

#### Path 7

In this case a specimen was sheared after it was heated at 90°C under undrained conditions. The heat-induced pore pressure caused the specimen to become OC with an OCR of 2.2. The details of specimen preparation of this case were as follows (*see* the history diagram in Fig. 10(c)). The specimen was first consolidated at 196 kPa and then kept overnight (step 1 to 3) as described in Path 1. Then, the specimen was heated at 90°C under undrained conditions; the heating was maintained until no more significant change in pore pressure was observed. Thereafter, the specimen was sheared.

The results of this case are compared with those of the previous cases in Fig. 13. It can be seen from this figure that stress-strain curves, for both small and large strain levels, of the specimens heated using different paths are comparable. In addition, the maximum deviator stresses for all the heating paths are of the same magnitude as those of unheated specimens as can be seen from Fig. 13(a). However, at a small strain level (Fig. 13(b)), the curves of the heated specimens, independent of the heating paths, are located above those of the unheated ones, i.e. the magnitudes of initial stiffness of heated specimens



Fig. 13. Results of undrained shear test of the specimens prepared under Path 5, Path 6, and Path 7 with OCR=2.2

are larger than those of unheated specimens. It should be further noted (from Fig. 13(c)) that the shear-induced pore pressure of Path 5 is higher than that of Path 7, and the pore pressure of Path 7 is higher than that of Path 6.

## **DEPENDENCY OF STRENGTH AND STIFFNESS ON TEMPERATURE**

Dependency of the maximum deviator stress on shear temperature of all the heating paths are summarized in Fig. 14. This figure clearly indicates that if the NC specimens were heated and then sheared at high temperatures, their maximum deviator stress increased with increasing temperature. However, if the specimens were cooled to room temperature and then sheared (Path 4), their maximum deviator stress did not differ from that of the unheated specimens. The figure further reveals that the maximum deviator stress of the heated OC specimens did not significantly differ from those of the unheated specimens.

Figure 15 shows the variation of the secant modulus at 0.1% strain with temperature for both NC and OC specimens. Again, the results of all the heating paths are included in this figure. It is clearly shown that the initial modulus for both NC and OC clays increased with in-



Fig. 14. Plots of maximum deviator stress versus temperature for both NC and OC specimens



Fig. 15. Plots of initial secant modulus versus temperature for both NC and OC specimens

creasing temperature. In addition, the heated and then cooled specimens also had a higher initial modulus than that of the unheated ones.

## **EXPLANATION OF THE DISCREPANCY AMONG THE PREVIOUS STUDIES**

Table 1 summarizes the results of the previous studies in terms of the methods of heating and the shear strength after heating. This table shows that all the studies which reported that heating caused a strengthening in clay used the drained heating method (Laguros, 1969; Nobel and Demirel, 1969; Houston et al., 1985), whereas those who found that heating induced weakening in clay can be divided into two groups. The first group used the undrained heating in their studies (Murayama, 1969; Sherif and Burrous, 1969), while the other used the drained heating (Mitchell, 1964; Hueckel and Baldi, 1990). The following paragraphs will point out a probable reason for the weakening reported by the first group.

As shown earlier, the undrained heating induces excess pore pressure in the specimens. This causes considerable reduction in the effective stress, and as a result, the strength and stiffness decrease. To demonstrate the effects of drainage on shear behavior, the stress-strain curve of Path 7 (undrained heating), Path 1 (drained heating), and unheated specimens are compared in Fig. 16. This figure clearly shows that if a study is performed using the drained heating method, the results would indicate that heating causes strengthening in clay. On the other hand, if a study is carried out using the undrained heating method (such as Murayama, 1969; Sherif and Burrous, 1969), the results would indicate that heating causes weakening in clay.

Although the above results reveal that the weakening reported by Murayama (1969) and Sherif and Burrous (1969) probably arose from the reduction of the effective stress due to the undrained heating used in their studies, the weakening found by Mitchell (1964) and Hueckel and Baldi (1990), however, requires further explanation.

Table 1. Summary o	f previous studies	on temperaturc effects
--------------------	--------------------	------------------------

Authors	Types of heating	Types of shearing	Strength after heating
Mitchell (1964)	D	U	X
Murayama (1969)	U	U	X
Sherif and Burrous (1969)	U	U	¥
Hueckel and Baldi (1990)	D	D	×
Laguros (1969)	D	U	1
Houston et al. (1985)	D	U	1
Nobel and Demirel (1969)	D	Direct shear	1

Notes: D = Drained, U = Undrained



Fig. 16. Comparison of stress-strain curves of specimens heated under undrained and drained conditions, and unheated specimen

## HEAT-INDUCED STRENGTH CHANGE VERSUS VOLUME CHANGE

This section discusses the relationship between the strength and the volume changes induced by heating. At this stage only qualitative, not quantitative, evaluation of such a relationship can be carried out since the exact void ratios of the specimens at various temperatures were not known due to the lack of knowledge about the density of the water in the clay pores at various temperatures. Variation in density of the pore water with temperature differs from that of free water (Derjaguin et al., 1986), and unfortunately, information about the density of the pore water is not quantitatively available at the present time. Since the magnitude of the void ratio change induced by heating is small, only 0.01 to 0.015 (Towhata et al., 1993), it would not be possible to detect the void ratio change without knowing the exact water density. Furthermore, due to this lack of knowledge about the nature of pore water, the volume change caused by heating cannot be reliably measured using a burette, since the volume of water drained from the specimen consists of not only the specimen's volume change, but also the volume of pore water expansion which is not known.

Due to these difficulties, it was decided to carry out a supplementary study on heat induced volume change using the conventional oedometer apparatus in which the change in void ratio can be reliably measured (Towhata et al., 1993). However, because of the limitation of the oedometer apparatus in which undrained conditions cannot be tested, heating Path 2 and Path 7 could not be measured. Furthermore, it was not possible to reproduce specimens with exactly the same void ratio: variation of void ratios of the specimens was of an order of 0.02, which was larger than the magnitude of the change in void ratio induced by heating. As a result, it was not considered reliable to measure the magnitude of the heat induced change in void ratio by comparing void ratio of a heated specimen with that of another unheated one. Thus, it was not possible to accurately measure the volume change of heating Path 6.

The study of volume change using oedometers (Towhata et al., 1993) revealed that if specimens were heated in accordance with Path 1 or Path 4, their void ratio decreased. However, if specimens were heated under Path 3, their void ratio increased. Although the volume change of Path 2 could not be directly measured as discussed above, it is believed that the heating caused void ratio reduction. This is because the pore pressures induced by shearing of the specimens of Path 2 were smaller than those of the unheated ones. This indicated that the specimens of Path 2 were "denser" than the unheated ones.

The changes in void ratio of the NC specimens induced by all the heating paths are summarized in Table 2 together with the changes in the initial stiffness and the shear strength.

Towhata et al. (1993) showed that generally the volume change of OC specimens heated using Path 5 (unloaded conditions) was dilative (except that of a lightly OC specimen with an OCR of 1.7 which was slightly contractive). Since the study of shear behavior of Path 5 was carried out using specimens with OCRs of 2.2, 4 and 8, it is believed that the heated induced volume changes of all the specimens should be dilative.

Although the heat induced volume changes of Paths 6 and 7 could not be directly measured as discussed above, it is believed that the volume change should be dilative for the following reasons. (1) The specimens of both Paths 6 and 7 were of the unloading type in which

 
 Table 2. Summary of changes in strength and stiffness versus change in volume of NC clay

Heating paths	Changes in void ratio	Changes in initial stiffness	Changes in shear strength
Path 1	X	1	1
Path 2	?	1	1
Path 3	1	1	1
Path 4	X	1	No change

Table 3. Summary of changes in strength and stiffness versus change in volume of OC clay

Heating paths	Changes in void ratio	Changes in initial stiffness	Changes in shear strength
Path 5	1	1	No change
Path 6	?1	1	No change
Path 7	?1	1	No change

Towhata et al. (1993) showed that heating generally causes a volume expansion. (2) The heated specimens had a higher shear induced pore pressure than the unheated ones did; indicating that before shearing the heated specimens were "looser" than the unheated ones.

The changes in void ratio of OC specimens induced by all the heating paths are summarized in Table 3 together with the changes in the initial stiffness and the shear strength.

# MECHANISMS OF TEMPERATURE EFFECTS ON SHEAR BEHAVIOR

## Nature of Shear Resistance

Resistance of clay against shear deformation consists of two distinct types; namely: micro-resistance and macro-resistance.

*Micro-resistance* is the resistance arising from bonding at interparticle contacts. The cause of bonding at the contacts has been a subject of controversy for a long time. The interaction at the contacts was believed to occur between solid and liquid phases by many investigators including Rosenqvist (1959), and Lambe (1960). Experimental investigations carried out later revealed, however, that the interaction could not have been of the liquid-solid type; instead, it had to occur between solid and solid (Christensen and Wu, 1964; Mitchell et al., 1968; Andersland and Douglas, 1970).

In bringing clay particles into contact, the absorbed water around clay particles would act as a barrier against the formation of the solid-solid interparticle contacts. It was estimated that the net energy required to remove the last monolayer of water when clay particles are brought together would be about  $0.1 \text{ J/m}^2$ . The corresponding pressure required to remove this layer of water may be as much as  $4 \times 10^5 \text{ kN/m}^2$  (van Olphen, 1963). This would act as a barrier against the formation of direct interparticle contact. As pointed out by Lambe and Whitman (1969), however, due to irregularities of particle surfaces the actual stresses at the contact points are much higher than the average applied stresses. Therefore, in the consolidation process, the water may be squeezed out from the contact points where the actual stress is high enough to overcome the resistance of absorbed water.

*Macro-resistance* is the resistance caused by movement of clay grains over others in the shear plane and is sometimes called "dilatancy effects". This movement creates a shear-induced volume change in drained testing. If volume change is not permitted, as in undrained testing, the effects of movement are manifested through the shear-induced pore pressure. In NC clay, the movement causes an average volume contraction or positive excess pore pressure, whereas for OC clay, these phenomena induce an average volume expansion or negative pore pressure. The magnitude of this resistance depends on many factors including: clay fabric, packing, and effective confining stress.

#### Mechanisms of Temperature Effects

It is commonly known that the energy of molecules of any substance is a function of temperature as explained by the kinetic theory. When temperature increases, the kinetic energy of molecules increases and, as a result, the net attraction energy between molecules decreases. This manifests itself, for example, through the decrease of viscosity of liquid with increasing temperature, and the weakening of metal as temperature increases. The increase of molecular energy also explains why the speed of chemical and physical processes increases with increasing temperature.

At first glance, an increase in temperature should have caused weakening in clay, since all the elements in clay mass—clay particles, pore water, absorbed water, etc. are weakened by an increase in temperature as explained by the kinetic theory. However, each of the elements is not independent. Instead, there are complex interactions between these elements. Shear resistance of clay is controlled by these interactions. Weakening of even one element would disturb the overall equilibrium of the interactions and would cause redistribution of stress among all of the elements. Even though all the elements are weakened by heating, the redistribution may transfer stress from weaker elements to stronger elements and may bring about an overall strengthening of the clay mass.

In order to understand the effects of temperature on the shear resistance of clay, it is necessary to know the basic behavior of these interactions. Unfortunately, it seems that these interactions are not well understood at present, and it is, therefore, difficult to evaluate the temperature effects on these interactions with certainty. However, based on available experimental results it is possible to postulate the most probable mechanism of temperature effects on the interactions and the shear resistance of clay. The following paragraphs will discuss the postulated mechanism of temperature effects.

The micro-resistance of clay should increase with increasing temperature since heating increases the number of the solid-solid contacts. The increase in the contacts can be explained by the fact that the strength of the absorbed water barrier around the clay particles is weakened by the increase in temperature, as explained above. Consequently, formation of the solid-solid contacts and, thus, the development of the micro-resistance is facilitated. It should be noted that the increase in micro-resistance by heating occurs in both NC and OC clays. The macro-resistance of clay can either increase or decrease with heating. The macro-resistance would increase if heating causes a volume contraction. On the other hand, it would decrease if heating induces a volume expansion.

In the NC state, the effects of temperature on the macro-resistance depend on the heating paths of the specimens. Table 2 indicates that macro-resistance of Paths 1 and 2 should increase with increasing temperature while that of Path 3 should decrease with heating. The results of shear tests, however, showed that the overall strength and stiffness of the specimens heated under Paths 1, 2, and 3 were almost the same and were higher than those of the unheated specimens. This indicates that the macroresistance probably plays a minor role in the shearing resistance, while the micro-resistance should be the main contribution to shear resistance of NC clay.

In OC state, Table 3 shows that heating generally induces volume expansion. Therefore, it should be expected that the macro-resistance of OC clay would decrease with increasing temperature.

As a result, it can be concluded that for the OC state, the micro-resistance would increase with an increase in temperature, whereas the macro-resistance would decrease with a rise in temperature. The higher initial stiffness of the heat specimens indicates that, at a small strain level, the micro-resistance would be the main contribution to the shear resistance of clay. However, the indifference in shear strength of heated and unheated OC clay reveals that the increase in micro-resistance is probably canceled by the decrease in the macro-resistance.

The fact that the initial stiffness of the heated and then cooled specimens (Path 4) is almost the same as that of the heated specimens indicates that the additional interparticle contacts formed by heating is not destroyed by the cooling process.

#### CONCLUSIONS

A series of consolidated undrained triaxial tests was conducted at various temperatures ranging from room temperature to 90°C using a triaxial apparatus. Several paths of heating and consolidation were used to gain insight into the effects of temperature on clay. The conclusions drawn from this study are described below.

1) In the NC state, the shear strength and stiffness of specimens heated under drained conditions are greater than those of unheated specimens, independent of the heating and consolidation paths. The volume change caused by heating does not account for the increase in strength and stiffness.

2) In OC state, the shear strength is not significantly affected by temperature changes, whereas the initial stiffness of the heated specimens, also independent of the heating and consolidation paths, is greater than that of the unheated ones.

3) The strengthening of clay can be reasonably explained by theorizing that heating weakens the absorbed water around clay particles and, thus, facilitates the formation of direct interparticle contacts which are the main contribution to resistance against any deformation.

4) The difference in drainage conditions during heating was the main factor that accounted for the discrepancies among the previous studies. Most, but not all, of the studies indicating that clays were weakened by heating were conducted using the undrained heating method in which heat-induced pore pressure significantly reduced the effective stress of the tested specimen, and, naturally, reduction in strength and stiffness was observed. On the other hand, those who reported that heating caused strengthening of clay used the drained heating method, in which the strength and stiffness increased as a result of the temperature effects discussed above.

#### ACKNOWLEDGMENT

The authors are deeply grateful to the Kajima Corporation for its financial support of the study described in this paper.

## REFERENCES

- 1) Ampadu, S. K. (1991): "Undrained behavior of kaolin in torsional simple shear," Doctoral Thesis, Institute of Industrial Science, University of Tokyo.
- Andersland, O. B. and Douglas, A. G. (1970): "Soil deformation rates and activation energies," Géotechnique, Vol. 20, No. 1, pp. 1-16.
- 3) Baldi, G., Hueckel, T. and Pellegrini, R. (1988): "Thermal volume changes of mineral-water system in low-porosity clay soil," Can. Geotech. J., Vol. 25, pp. 807-825.
- 4) Bergenstahl, L., Gabrielsson, A. and Mulabdic, M. (1994): "Changes in soft clay caused by increases in temperature," Proceeding 13th ICSMFE, Vol. 4, pp. 1637-1640.
- 5) Campanella, R. G. and Mitchell, J. K. (1968): "Influence of temperature variations on soil behavior," J. Soil Mech. and Found. Div., ASCE, Vol. 94, No. 3, pp. 709-734.
- Christensen, R. W. and Wu, T. H. (1964): "Analysis of clay deformation as a rate process," J. Soil Mech. and Found. Div., ASCE, Vol. 90, No. 1, pp. 125-157.
- Derjaguin, B. V., Kasasev, V. V. and Khromova, E. N. (1986): "Thermal expansion of water in fine pores," J. of Colloid and Interface Science, Vol. 106, pp. 586-587.
- Houston S. L., Houston W. N. and Williams, N. D. (1985): "Thermo-mechanical behavior of seafloor sediments," J. Soil Mech. and Found. Div., ASCE, Vol. 111, No. 11, pp. 1249-1263.
- 9) Hueckel, T. and Baldi, G. (1990): "Thermoplasticity of saturated clays: Experimental constitute study," J. Geotech. Engrg., ASCE, Vol. 116, No. 12, pp. 1178–1769.
- 10) Kuntiwattanakul, P. (1991): "Effects of high temperature on mechanical behavior of clays," Doctoral Thesis, Department of Civil Engineering, the University of Tokyo.
- Laguros, J. G. (1969): "Effect of temperature on some engineering properties of clay soils," Effects of Temperature and Heat on Engineering Properties of Soils, Special Report 103, Highway Research Board, Washington, D.C., pp. 186-193.
- 12) Lambe, T. W. (1960): "A mechanistic picture of shear strength in clay," Proc. ASCE Research Conf. on Shear Strength of Cohesive Soils, Boulder, Colorado, pp. 555-580.
- Lambe, T. W. and Whitman, R. V. (1969): Soil Mechanics, John Wiley and Sons, New York.
- 14) Mitchell, J. K. (1964): "Shearing resistance of soils as a rate process," J. Soil Mech. and Found. Engrg. Div., ASCE, Vol. 90, No. 1, pp. 231-251.
- 15) Mitchell, J. K., Campanella, R. G. and Singh, A. (1968): "Soil

creep as a rate process," J. Soil Mech. and Found. Engrg. Div., ASCE, Vol. 94, No. 1, pp. 29-61.

- 16) Mitchell, J. K. (1976): Fundamentals of Soil Behavior, John Wiley and Sons, New York, N.Y.
- 17) Murayama, S. (1969): "Effect of temperature on the elasticity of clays," Effects of Temperature and Heat on Engineering Properties of Soils, Special Report 103, Highway Research Board, Washington, D.C., pp. 194-203.
- 18) Noble, C. A. and Demirel T. (1969): "Effect of temperature on strength behavior of cohesive soil," Effects of Temperature and Heat on Engineering Properties of Soils, Special Report 103, Highway Research Board, Washington, D.C., pp. 204-219.
- 19) Poorooshasb, F. and James, R. G. (1989): "Centrifuge modeling of heat-generating waste disposal," Can. Geotech. J., Vol. 26, pp. 640-652.
- 20) Radhakrishna, H. S., Chan, H. T., Crawford, A. M. and Lau, K. C. (1989): "Thermal and physical properties of cadidate buffer-backfill materials for nuclear fuel waste disposal vault," Can. Ge-

otech. J., Vol. 26, pp. 629-639.

- 21) Rosenqvist, I. Th. (1959): "Physico-chemical properties of soils: soil-water systems," J. Soil Mech. and Found. Div., ASCE, Vol. 85, No. 2, pp. 31-53.
- 22) Sherif, M. A. and Burrous, C. M. (1969): "Temperature effect on unconfined shear strength of saturated cohesive soils," Effects of Temperature and Heat on Engineering Properties of Soils, Special Report 103, Highway Research Board, Washington, D.C., pp. 267-271.
- 23) Towhata, I., Kuntiwattanakul, P., Seko, I. and Ohishi, K. (1993): "Volume change of clays induced by heating as observed in consolidation tests," Soils and Foundations, Vol. 33, No. 4, pp. 170-183.
- 24) Tsuchida, T. (1990): "Study on determination of undrained strength of clayey ground by mean of triaxial tests," Technical Note of The Port and Harbor Research Institute, No. 688, Ministry of Transportation (in Japanese).
- 25) van Olphen, H. (1963): An Introduction to Clay Colloid Chemistry, Wiley Interscience, New York.