XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

BEHAVIOR OF CLAYS UNDERGOING ELEVATED TEMPERATURE

COMPORTEMENT DE L'ARGILE A HAUTE TEMPERATURE

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SYNOPSIS: This paper concerns with the effects of high-temperature environments on the mechanical behavior of clays. Heating dry clay powder, firstly, indicated that no change occurred to the nature of clay. Secondly, however, when clay was mixed with water and consolidation tests were run, heating immediately triggered a volume contraction and the rate of consolidation was accelerated as well. Triaxial tests revealed, thirdly, that both modulus and shear strength of specimens were improved by heating. With these observations, the authors proposed hypotheses to explain the detected behavior of heated clays. Reasoning based on the hypotheses was consistent with the results of experiments that were carried out for their verification.

INTRODUCTION

This study is related to an underground repository of nuclear waste fuels. One of the candidate repositories is an underground cavern where the waste fuel is placed and backfilled by bentonite, which swells to fill the cavern completely and prevent leakage of the radioactive material. It has been feared that the backfill clay might be affected by the elevated temperature generated by the radio activity. In this regard, laboratory testings were carried out to understand the effects of high temperature on the behaviour of clays.

APPARATUS, MATERIALS AND SAMPLE PREPARATION

Consolidation tests under high temperature were performed by using a conventional oedometer resting in a hot water bath. A heater with a thermostat maintained the water temperature in the bath at a specified level. A propeller driven by a motor stirred the heated water to make its temperature uniform. The thermal distortion of the apparatus was calibrated to obtain a precise deformation of soil samples.

Fig.1 shows a triaxial apparatus which consists of double chambers. The inner chamber is filled up with water that is heated during tests. Both thermostat and propeller are provided for temperature control. The outer chamber is filled with pressurized air functioning as a thermal insulator.

The bentonite clay has a liquid limit of 450% and a plasticity index of 423%. This material was used, however, in limited number of tests because of its long time needed for consolidation of samples. Most testings were performed on "MC clay" that is similar to kaolin. The properties of this clay are; liquid limit = 70% and plasticity index = 29%.

Consolidation and shear specimens were prepared from a slurry. Clay powders were mixed with distilled water and de-aired under vacuum in order to achieve 100% saturation. Thereafter, the clay was consolidated one-dimensionally.

EFFECTS OF HEATING ON DRY POWDER OF CLAY

Study was initiated by heating dry powder of clays at 60, 110, and 200° C for five days. After cooling, this powder was mixed with

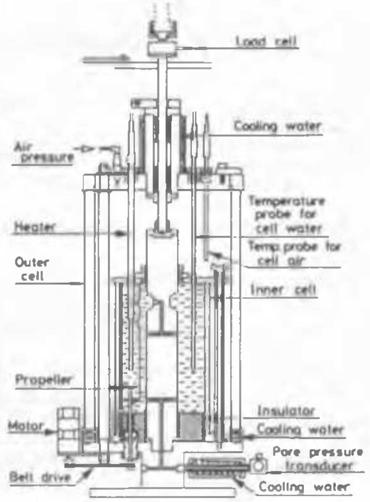

Fig.1 Triaxial apparatus with heater.

distilled water and stored for one week.

The test results in Fig.2 does not show significant effects of preheating powders on the liquid limit of clays. Since preheating did not influence the plastic limit and the unconfined compression strength, either, it was concluded that preheating of clay powders at maximum 200° C does not affect the engineering properties of the clays. Thus, the research interest was shifted to the thermal effects on the interaction between clay and pore water.

CONSOLIDATION TESTS UNDER ELEVATED TEMPERATURE

This section demonstrates the consolidation behavior of MC clay. Heating at between the room temperature and 90° C started after the completion of the primary consolidation.

Fig.3 demonstrates the thermal contraction of clay, similar to Paaswell (1967), Campanella and Mitchell (1967) and Baldi et al. (1988), when a normally consolidated sample was subject to a stress increment from 80 to 160 kPa and a temperature rose by steps from 22 through 40 and 60 to 90° C. Fig.4 indicates that one cycle of heating and cooling between 22 and 90° C left a residual volume change. Thus, the thermal volume change of clay is irrecoverable.

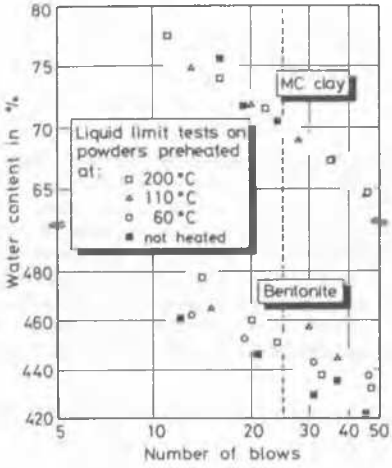

Fig.2 Variation of liquid limit with heating.

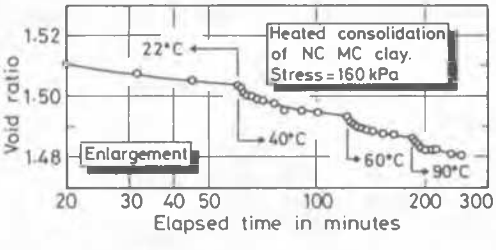

Fig.3 Time history of consolidation test.

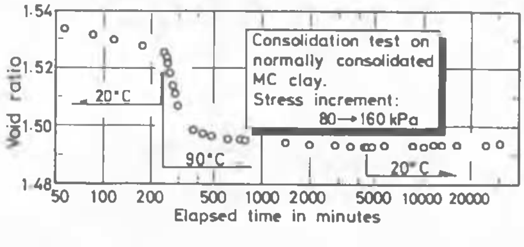

Fig.4 Effects of thermal cycle on clay volume.

Similar tests were repeated under a variety of stress with a stress increment ratio = 1.0. Fig.5 summarizes the decrease of void ratio induced by heating. Except the case of 40 kPa, the thermal volume change varies with the temperature, independent of the stress level as shown by Demars and Charles (1982).

Fig.6 compares the e vs. log P relationship of samples which were heated at 90° C under 160 kPa for periods ranging from one day to two months and further continued the normal consolidation under higher pressure at 90° C. The longer period of heating at 160 kPa caused the greater amount of volume contraction.

It is interesting that, under pressure levels above 160 kPa, the data of heated samples lie above the normal consolidation curve of unheated samples. This phenomenon is more profound for the longer period of heating at 160 kPa. Therefore, it seems that the clay specimen obtained an extra stiffness of its skeleton in the course of prolonged heating at 160 kPa so that it can sustain higher pressure later on at the same void ratio. This phenomenon is not

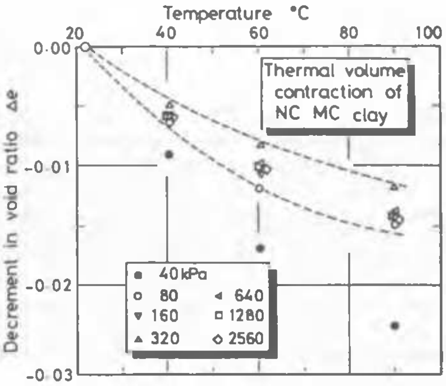

Fig.5 Volume contraction due to heating.

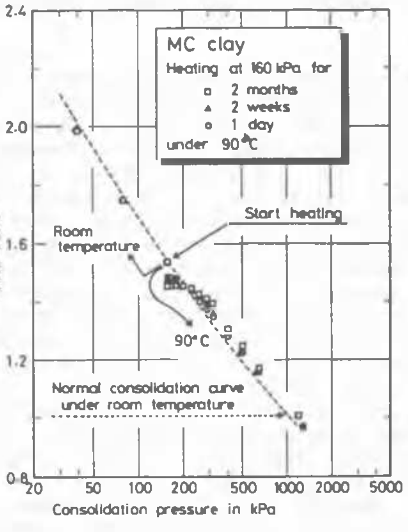

Fig.6 The e-log P curve of heated specimen.

connected with cementation, contrary to Tsuchida et al. (1991), because no cementing material was supplied into the specimen.

ON PERMEABILITY

The coefficient of permeability 'k' was calculated by applying the conventional $\sqrt{t}$ method to consolidation test results.

In Fig.7, the obtained permeability is normalized by that at 20° C at the identical void ratio. Taylor's equation shows that permeability depends on a function, F, of void ratio (e), unit weight of pore liquid (γ), and its viscosity (μ) (Houston and Lin, 1987);

$$k = \text{const.} * F(e)\,\frac{\gamma}{\mu} \qquad (1)$$

The constant parameter in Eq.1 stands for the effects of, e.g., the geometry of the pore water channel. In the present study, the thermal variation of γ and μ of pure water was substituted in Eq.1, while a fixed void ratio was employed, and a theoretical variation of k with temperature was obtained, shown by a solid curve in Fig.7. Most of the predicted increase of k was made by the decrease of water viscosity upon heating. Calculation cannot, however, fully explain the experimental increase in k. Moreover, since Figs.3, 4 and 6 reveal a minor thermal volume contraction, no significant distortion in pore geometry is likely.

HYPOTHESES ON THERMAL EFFECTS OF CLAY

The surface of clay particles has a negative electric charge and electric dipoles of water molecules (Fig.8) are adsorbed to it (Mitchel, 1976). This water has a higher viscosity (Rosenqvist, 1959) and prevents easy contact of clay particles upon compression. Theories as Guoy-Chapman's on the behavior of adsorbed ions are of reversible nature and cannot handle the irrecoverable experimental observation in Fig.4. Therefore, authors hypothesize that

1) Adsorbed water molecules can get out of the electric field, when they gain a sufficient energy thermo-dynamically through heating.
2) When water molecules have escaped, adjacent clay grains can get contact with each other and reduce the void ratio, thus developing a secondary compression.
3) Water molecules can obtain a sufficient escape energy more easily when heated. Therefore, heating accelerates the secondary compression. Apparently, this heating effect is independent of stress (Fig.5).
4) Since the pore loses adsorbed water and is filled with free water of lower viscosity, permeability increases on heating (Fig.7).

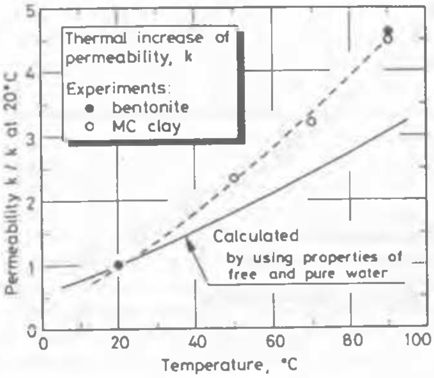

Fig.7 Increase of permeability by heating.

These hypotheses were supported by running a consolidation test of bentonite with normal octane as the pore liquid. With its viscosity and unit weight being 56% and 70% of those of pure water, respectively, octane has a symmetric structure of molecule (Fig.8) and, hence, does not form a strong dipole. Thus, no thick layer of adsorbed molecules is created and soil samples should behave like heated clay with water, whatever the temperature may be.

Fig.9 shows the test results. The consolidation with octane at room temperature was completed within 20 seconds, that is remarkably shorter than that with water. Further, consolidation time is independent of the temperature. These findings support the authors' hypotheses. The minor thermal volume change observed upon heating suggests that an electric dipole was induced to a limited extent by the electric field near the clay surface.

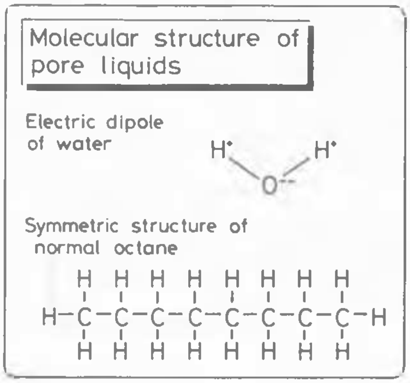

Fig.8 Molecules of water and octane

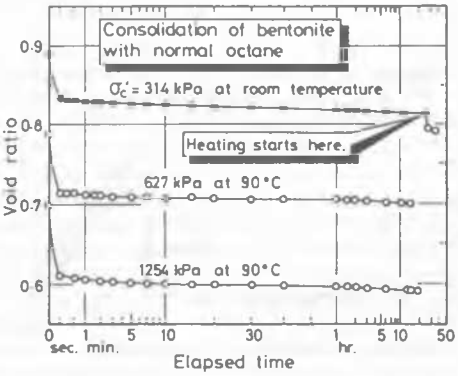

Fig.9 Consolidation test by using octane.

TRIAXIAL TESTING

Triaxial undrained tests (CU) were conducted by using the thermal triaxial apparatus (Fig.1). MC clay specimens were consolidated isotropically under 196 kPa, heated at 50, 70, and 90° C under drained conditions, and sheared in undrained manners, undergoing high temperature. Fig.10 demonstrates that both modulus and strength were improved by heating, while the excess pore water pressure during shear was reduced.

Triaxial drained tests (CD) at 90° C are indicated in Fig.11. Apparently heating increaseed the stiffness of MC clay, while its shear-induced volume change became less contractive.

The aforementioned hypotheses infer that drained heating accelerates the secondary compression and increases the number of grain contacts, thereby improving the mechanical property of clay. This reasoning is consistent with test data in Figs. 6, 10, and 11.

CONCLUSION

The study on the effects of heating on clay behavior has led to the following conclusions;

1) Preheating up to 200° C does not affect clay powders.
2) Rate of consolidation is accelerated partly by reduced viscosity of pore water and partly by the decrease of adsorbed water.
3) Heating improves shear modulus, strength, and dilatancy or pore pressure rise of clay.
4) The observed temperature effects are explained by proposing hypotheses on thermal behavior of water molecules.

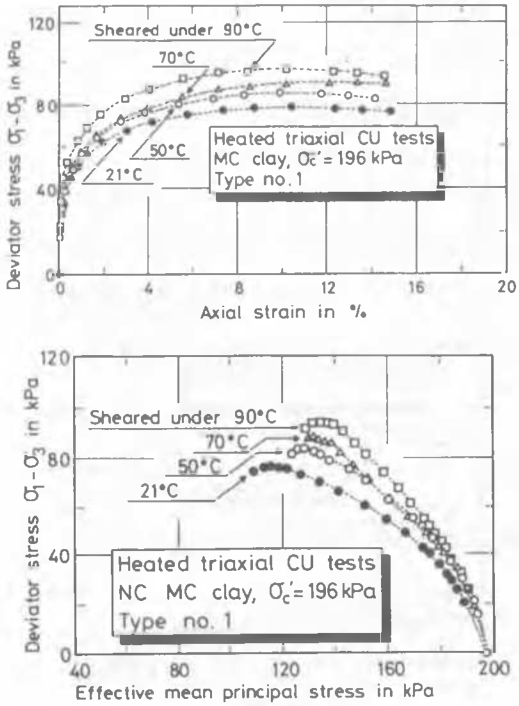

Fig.10 CU triaxial tests on heated MC clay.

ACKNOWLEDGEMENTS

The authors express their gratitudes to Messrs. H.Kobayashi, I.Seko, and K.Oh-ishi; former students of the University of Tokyo; whom the investigation was run in cooperation with.

REFERENCES

Mitchell,J.K. (1976) Fundamentals of Soil Behavior, John Wiley and Sons, pp.103.

Baldi,G. et al. (1988) Thermal Volume Change of the Mineral-Water System in Low-Porosity Clay Soils, Can. Geotech. J., Vol.25, pp.807-825.

Campanella,R,G. and Mitchell,J.K. (1967) Influence of Temperature Variation on Soil Behavior, J. Soil Mech. Found. Div., ASCE, Vol.94, SM3, pp.709-734.

Demars,K.R. and Charles,R.D. (1982) Soil Volume Changes Induced by Temperature Cycling, Can. Geotech. Journal, Vol.19, pp.188-194.

Houston,S.L. and Lin,H.D. (1987) A Thermal Consolidation Model for Pelagic Clays, Marine Geotechnology, Vol.7, pp.79-98.

Paaswell,R.E. (1967) Temperature Effects on Clay Soil Consolidation, J. Soil Mech. Found. Div., ASCE, Vol.93, SM3, pp.9-22.

Rosenqvist,I.Th. (1959) Physico-chemical Properties of Soils: Soil-Water Systems, J. Soil Mech. Found. Div., ASCE, Vol.85,SM2, pp.31-53.

Tsuchida,T. et al. (1991) Effect of Aging of Marine Clay and its Duplication by High Temperature Consolidation, Soils and Found., Vol.31, No.4, pp.133-147.

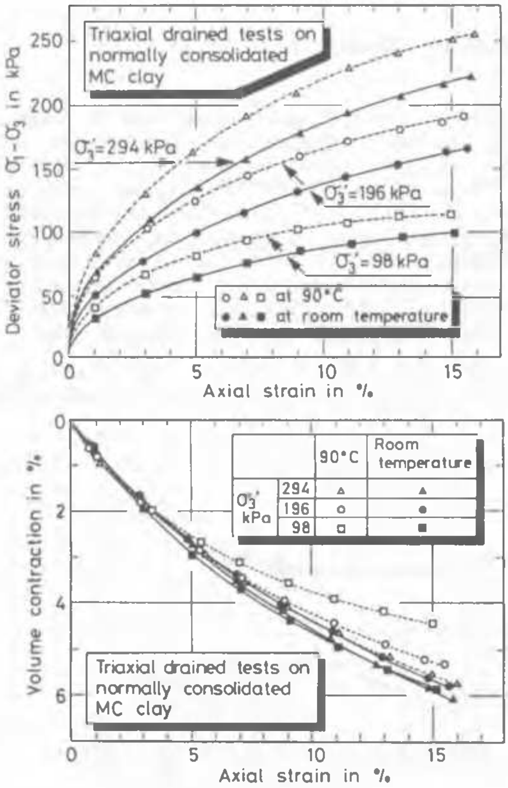

Fig.11 CD triaxial tests on heated MC clay.