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Constant rate of strain consolidation properties of clayey soil at high temperature

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ABSTRACT : A series of constant rate of strain consolidation tests on remolded saturated clayey soil were carried out by using three types of ambient temperature conditions and strain rates. The magnitudes of cosolidation obtained from the high temperature consolidation tests were independent upon the magnitudes of strain rates used. The rate of consolidation obtained during normal consolidation region became greater under elevated temperature condition because of the decrease in viscosity of soil skeleton and pore water.

1. INTRODUCTION

In the case of constant rate of strain consolidation tests on saturated clayey soil, the magnitude and rate of consolidation of soil are obtained by measuring the axial loading pressure and the excess pore water pressure developed at the impervious end when the specimen is continuously deformed at constant rate under single drainage condition. The JSSMFE standard for this test method has been prepared by the technical committee(JSSMFE, 1992).

The consolidation properties of clayey soil obtained by this test method are known to be related with the viscous properties of soil skeleton dependent upon the magnitude of strain rate used (Olson, 1985).

Temperature dependency of the consolidation characteristics of clayey soils have been also investigated for a long time (Mitchell,1993). Both of the magnitude and rate of consolidation were shown to be influenced by the variation of temperature and related with the viscous properties of soil skeleton and pore water.

In this paper a series of constant rate of strain consolidation tests on remolded saturated clayey soil were carried out by using three types of ambient temperature conditions and strain rates, since the viscous properties of soil skeleton and pore water were considered to be also dependent upon the temperature conditions.

The influences of the decreased viscosity of the clay skeleton and pore water due to the elevation of the ambient temperature on the constant rate of strain consolidation characteristics of clayey soil have been investigated qualitatively and quantitatively by using the experimental results mentioned above.

2. CONCISE REVIEW OF PREVIOUS STUDIES

2.1 CONSTANT RATE OF STRAIN CONSOLIDATION TESTS

Leroueil et al.(1985) conducted various types of oedometer tests by using the natural clayey soils, including constant rate of strain consolidation tests (CRS tests, abbreviated in the following sections). Typical results are presented in Fig.1. Fig.1 shows that, at a given strain, the higher the strain rate, the higher the effective stress. They deduced the existence of a unique stress-strain-strain rate relationship of natural clayey soils from the numerous experimental results.

2.2 HIGH TEMPERATURE CONSOLIDATION TESTS

The effect of temperature on the consolidation of illite is shown in Fig.2 (Campanella and Mitchell,

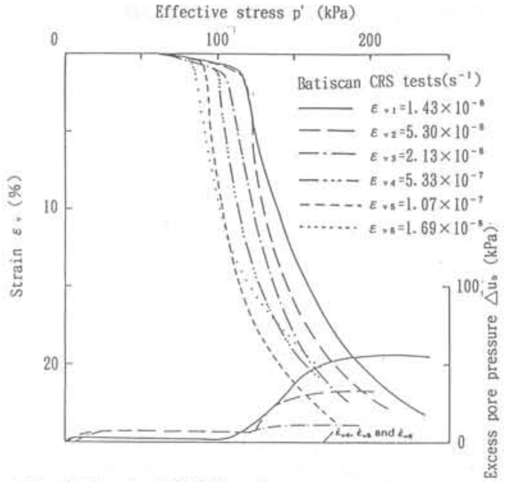

Fig.1 Typical CRS oedometer tests on Batiscan Clay (Leroueil et al,1985)

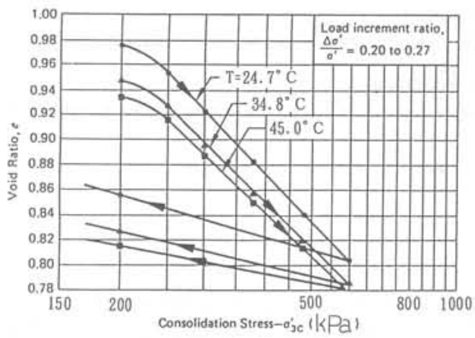

Fig.2 Effect of temperature on isotropic consolidation behavior of saturated illite (Campanella and Mitchell,1968)

1968). Equal compression indices were measured for greater than 200 kPa. As consolidation was started from the same initial water content for all three specimens, the clay at higher temperatures must have been more compressible at lower pressures to account for the void ratio differences observed.

Recently Tsuchida et al.(1991) indicated the possibility of duplicating the natural aging of marine clays by consolidating clay slurry at high temperature and cooling it after the completion of consolidation.

Towhata et al.(1993) also carried out the experimental investigations on the volume change characteristics of clay under elevated temperature conditions and demonstrated their dependency upon the over-consolidation ratio of clay specimen.

3. EXPERIMENTAL PROCEDURES AND CALCULATION OF TEST RESULTS

A clayey soil sample used in this study was obtained from marine clayey soil deposit at the offshore area of Tokyo International Air-port (Haneda, Tokyo). The physical properties of the clayey soil sample are listed in Table 1 and its plasticity is observed to be relatively high.

The soil sample was thoroughly mixed with distilled water at the water content corresponding to the value of two times of its liquid limit. The clayey soil slurry was then one-dimensionally consolidated incrementally up to the vertical effective stress of 98(kPa) in the stainless mould (Diameter=25(cm)) for a week. The specimens (diameter=6(cm), height=2(cm)) were prepared by using reconstituted clayey soil sample block prepared by the re-consolidation mentioned above.

The system setup of the experimental apparatus is shown in Fig.3. Although the thermal sensor for measuring the temperature of the specimen was not provided in the consolidometer, the temperature of the specimen was kept constant at the prescribed value after the long duration of the heating of the water in the bath. The prescribed values of hot water temperature used in the experiments were 20, 50 and 80 (°C).

The constant rate of strain consolidation tests were carried out under the application of back pressure of 196 (kPa) from the top of the specimen. The strain rates used in the experiments are 0.05, 0.25 and 0.5 (%/min) calculated based upon the initial height of the specimen.

Table 1: Physical properties of soil sample

Density of soil particle ρ_s(g/cm^3)	2.65
Liquid limit w_L(%)	104.0
Plasticity index I_P	62.7

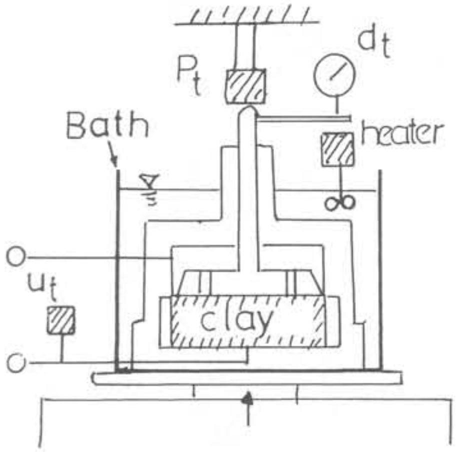

Fig.3 The system setup of the experimental apparatus

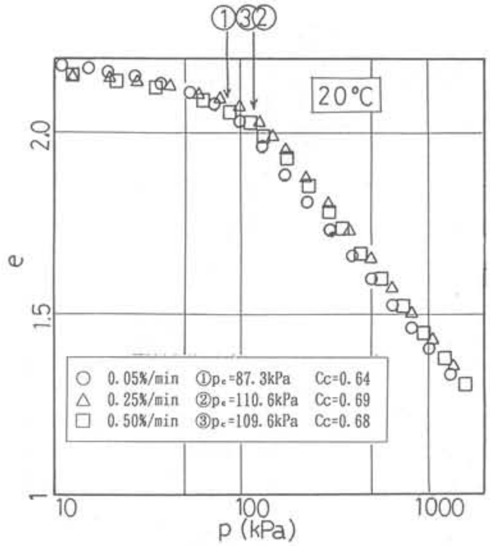

Fig.4 ***e*−log *p*** **curves obtained from three types of strain rates CRS tests under *20(° C)***

The magnitude of consolidation pressure p (kPa) during CRS loading was obtained from the following equation (1), assuming the parabolic distribution of the axial strain or effective stress across the specimen.

$$p = \sigma_t - \frac{2}{3} \cdot u_t \ (1)$$

in which $\sigma_t = P_t/A(P_t$:axial loading force, A: cross-sectional area of the specimen) is the axial loading pressure and u_t is the excess pore pressure developed at the impervious bottom end of the specimen at the elapsed time t since the initiation of loading.

The value of volume compressibility m_v (m^2/kN) was calculated as the following equation (2).

$$m_v = \frac{\Delta H/\bar{H}}{\Delta\sigma} \ (2)$$

in which $\Delta H = d_t - d_{t'}$(cm) ($d_t, d_{t'}$:the deformation of the specimen at time t and $t'(= t + \Delta t$: Δt (min) is time interval used in the calculation of test results)), $\bar{H}$ is the arithmetic average value of the height of the specimen at time t and t' and $\Delta\sigma$ (kPa) is the increment of the axial loading pressure between t and t'.

The value of consolidation coefficient c_v (cm^2/d) is calculated as follows, following the analytical solution of c_v obtained by Wissa et al. (1971).

$$c_v = \frac{\Delta\sigma\bar{H}^2}{2\bar{u}\Delta t} \times 1440 \ (3)$$

in which $\bar{u}$ is the average value of the excess pore pressure developed at the elapsed time t and t'.

The pore water pressure sensor was connected to the stainless lead pipe provided at the outside of the hot water bath, which transmitted the pore water pressure developed at the bottom end of the specimen. Therefore the erroneous effects of the high water temperature on the measurement results of pore water pressure were considered to be negligible small.

4. CONSOLIDATION CHARACTERISTICS OF CLAYEY SOIL UNDER CRS LOADING AND HIGH TEMPERATURE

Fig.4 compares the $e - \log p$ curves obtained from three types of strain rates CRS tests under 20(°C). Similar $e - \log p$ curves under 50(°C) and 80(°C) are also shown in Fig.5 and Fig.6. Although the differences among the $e - \log p$ curves dependent upon the strain rates obtained in any

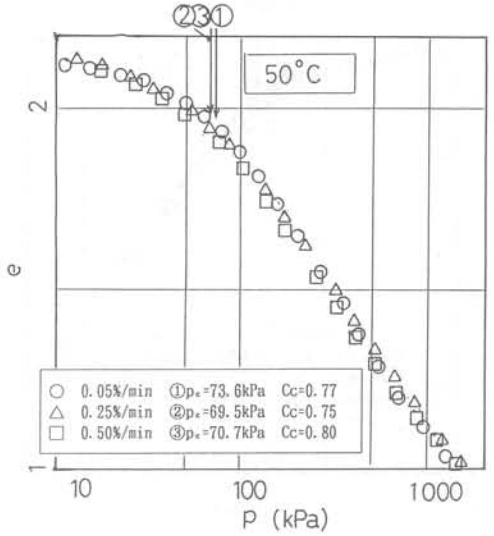

Fig.5 $e-\log p$ **curves obtained from three types of strain rates CRS tests under** *50(° C)*

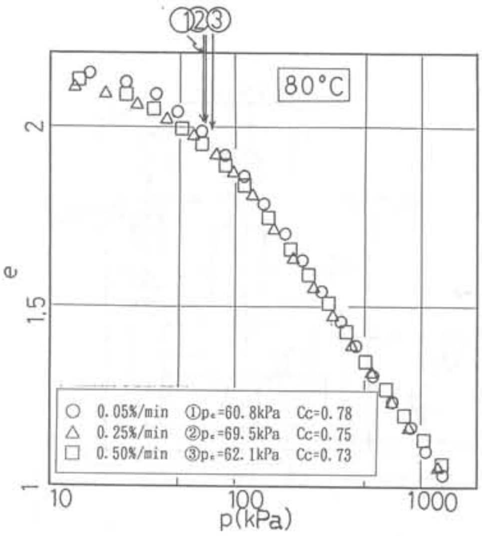

Fig.6 $e-\log p$ **curves obtained from three types of strain rates CRS tests under** *80(° C)*

cases are not so large as shown in Fig.1, the values of consolidation yield stress p_c and compression index C_c in each case are obtained and indicated in the figures. The values of p_c in the cases of 0.25 and 0.5 (%/min) are greater than that for 0.05 (%/min). The values of C_c are almost the same in any cases independent upon the strain rates used. It is evident from Fig.5 and Fig.6 that $e-\log p$ curves obtained from three types of strain rates CRS tests coincide with each other and are independent upon the strain rates used in the tests under the elevated temperature conditions.

The decreased viscosity of soil skeleton due to the elevation of ambient temperature affects the geometric shape of $e-\log p$ curves, *i.e.* the magnitudes of consolidation obtained from CRS tests.

Fig.7 shows the variations of $e-\log p$ curves dependent upon the elevation of ambient temperature for the strain rate of 0.05(%/min). It is noted that the values of void ratio obtained from high temperature consolidation tests at low effective stresses are relatively smaller than that for 20(°C) and the consolidation yield stress p_c becomes smaller as mentioned before. The values of compression index C_c under high temperature conditions are large compared with that for

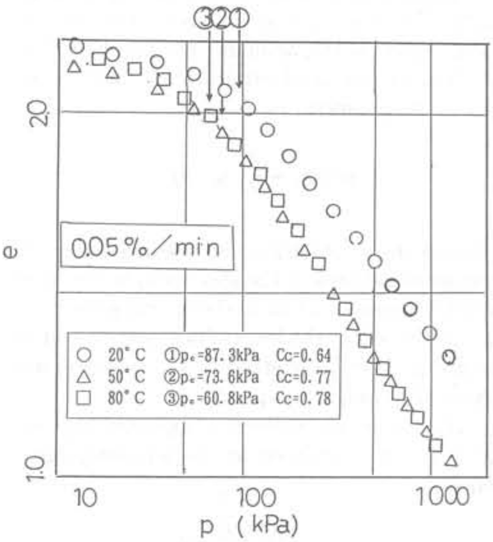

Fig.7 $e-\log p$ **curves dependent upon the elevation of ambient temperature for the strain rate of** *0.05(%/min)*

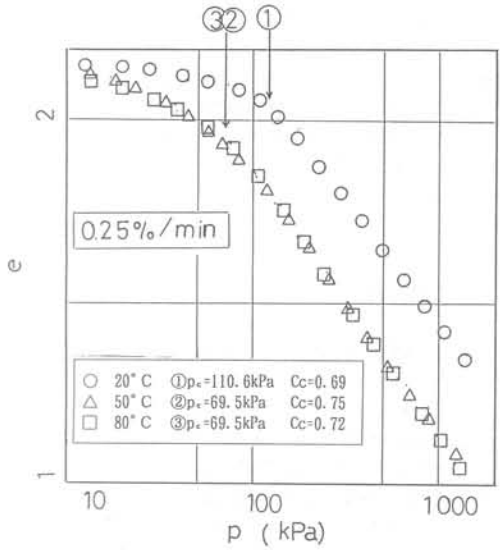

Fig.8 ***e*−log *p* curves dependent upon the elevation of ambient temperature for the strain rate of *0.25(%/min)***

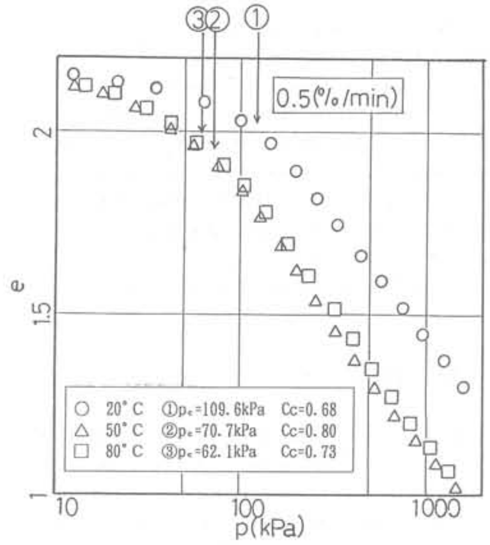

Fig.9 ***e*−log *p* curves dependent upon the elevation of ambient temperature for the strain rate of *0.5(%/min)***

20(°C). Similar relationships are also shown in Fig.8 and Fig.9 for other strain rates of 0.25 and 0.5 (%/min).

The relative positions of $e - \log p$ curves obtained from CRS tests under high temperature conditions are almost the same as the $e - \log p$ curves obtained from incremental loading consolidation tests as shown in Fig.2. The void ratio decrease of high temperature specimen at lower pressure is greater than that of 20(°C) specimen because of the decreased viscosity of clayey soil skeleton and pore water. Since the viscosity of clayey soil skeleton decreases remarkably due to the elevation of temperature, the variations of resistance of soil skeleton against the deformation associated with the change of rate of strain become presumably negligible small.

Fig.10 and Fig.11 compare the variations of $\log m_v - \log p$ and $\log c_v - \log p$ relationships against the change of temperature condition under 0.25(%/min) CRS loading. Although it is difficult to note the differences in the consolidation characteristics during over-consolidation region, the values of m_v during normal consolidation region are almost the same as the value obtained from conventional incremental loading consolida-

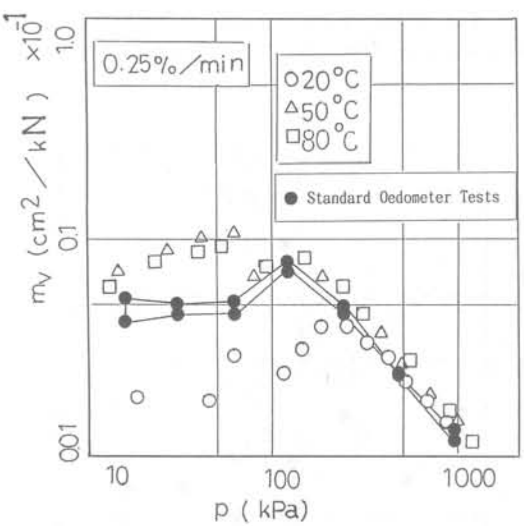

Fig.10 log *m*$_v$ ~ log *p* relationships against the change of temperature condition under *0.25(%/min)* CRS loading

tion tests at room temperature. The differences of m_v values due to the variations of temperature conditions are considered to be small.

The values of c_v obtained from 0.25(%/min) CRS tests are greater than those of conventional tests and become greater as the temperature is elevated. It is evident that the rate of consolidation becomes greater according to the decreased viscosity of soil skeleton and pore water associated with the elevation of temperature.

5. CONCLUSIONS

It is concluded from a series of constant rate of strain consolidation test results under various temperature conditions that:

(1) The geometric shape of $e - \log p$ curves, *i.e.* the magnitudes of consolidation obtained from high temperature CRS tests are almost the same as each other and independent upon the rates of strain used in the tests. The values of compression index C_c under high temperature conditions are large compared with the value under room temperature of 20(°C).

(2) The values of m_v are almost the same as those obtained from the conventional incremental loading consolidation tests and the differences of m_v values due to the variations of temperature conditions are considered to be small.

(3) The values of c_v obtained from high temperature CRS tests become greater than those of room temperature condition tests and indicate the decrease of viscosity of soil skeleton and pore water.

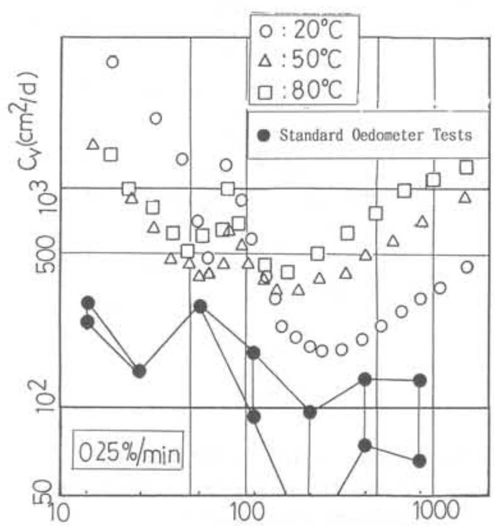

Fig.11 $\log c_v \sim \log p$ relationships against the change of temperature condition under *0.25(%/min)* CRS loading

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