Temperature Effects on One-Dimensional Consolidation Behavior of a Clay

by

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Abstract

Two kinds of oedometer tests were carried out on a fine-grained soil sample: one is the sest in which the virgin loading and the unloading were made at the temperature of 75°C and the subsequent reloading at the room temperature; and in the other the temperature was held constant at the room temperature. The effects of the high temperature and the high-temperature history on the compressibility and the behavior in consolidation are examined.

The following results were obtained:

1) The compression index becomes larger by heating.

2) Specimens with the high-temperature history show apparent preconsolidation behavior.

3) The rate of secondary compression is affected by the temperature only at the low level of the pressure.

4) The rate of primary consolidation, c_v' is higher when consolidated at the high temperature than at the low one.

The reason why c_v' can differ under different temperatures is discussed by applying the Terzaghi's theory of consolidation and the Taylor's equation for the coefficient of permeability. It is shown that these theories can explain an aspect of the temperature dependence of c_v'.

Key words : Cohesive soil／Consolidation／Permeability／Temperature effect

1. INTRODUCTION

The effects of temperature on the volume change behavior of soils have been studied by many researchers. The previous studies are summarized as follows:

1)Volume contraction occurs with the increase in temperature and volume expansion occurs with the decrease in it. (Lambe,1958; Campannela and Mitchell,1968)

2)There are different results on the effects of temperature upon compressibility: Campanella and Mitchell(1968) showed, by consolidating an illite clay under different temperatures in the range from 24 to 51°C, that identical values for compression index C_c were measured at different temperatures, whereas Plum and Esrig (1969) showed that a higher value for C_c was obtained at the temperature of 50°C than at that of 24°C for the same kind of clay to that used in Campanella and Mitchell(1968).

3)Void ratio can be smaller, at any consolidation pressure, when consolidated under higher temperature (Gray,1936).

Recently Tsuchida et al.(1989) showed that the consolidation at the temperature as high as 75°C on the sample reconstituted from a natural undisturbed clay sample could revive the behavior similar to that of the undisturbed sample. The specific behavior to undisturbed clays are attributed to the effects of the aging that they have been subjected to. Some aging effects can be given to reconstituted clays by carrying out the long term consolidation on them as in Leonards (1958). The results shown by Tsuchida et al.(1989) suggest that the aging effects can be reappeared in laboratory by heating remolded samples instead of by carrying out long-term consolidation tests.

In this paper, by presenting the results from those oedometer tests in which temperature was varied, effects of temperature on the compression index in the normal consolidation state and on the rates of primary and secondary consolidation are discussed. In particular, a possible cause of the temperature effect on the coefficient of primary consolidation will be discussed by applying the Terzaghi's theory of consolidation and a Kozeny-Carman type of equation for the coefficient of permeability (Taylor,1948).

2. EXPERIMENTS

2.1 Test Equipment

In Fig.1, the test equipment used in this study is shown. A standard consolidometer is placed in a water bath. A thermometer and a thermostat sensor were set to measure and control the temperature with accuracy during tests.

Temperature was measured outside but near the consolidation ring. The temperature was so satisfactorily controlled that its fluctuation was less than ±2°C. A displacement transducer was placed far from the bath so as not to be affected by possibly high temperature in the bath.

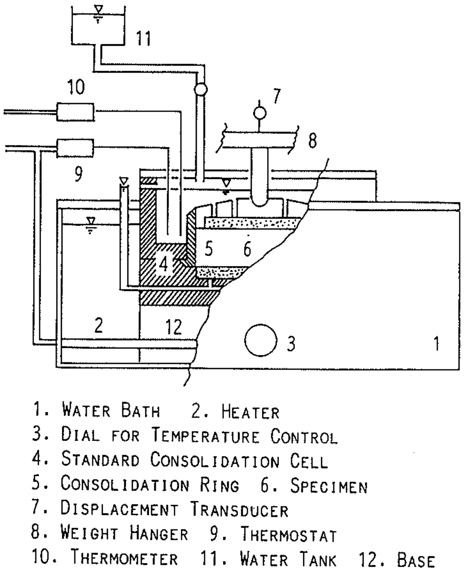


Fig.1: Schematic presentation of the test equipment used.

2.2 Sample used

A kaolinitic clay called Fujinomori Clay was used as the sample (see Fig.2). The clay powder was mixed and remolded with water in a mixing batch. A pair of specimens were prepared from the slurry mixed in one batch. Thus the initial water content of any pair of specimens could be identical therefore. Four pairs, No.1 to 4, of different water contents from 59 to 109% were prepared. The description of specimens is given in Table 1 as well as the testing condition.

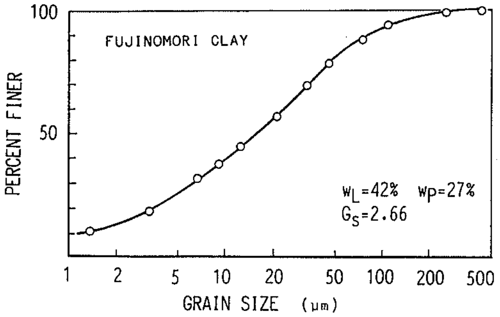


Fig.2: Grain size distribution and consistency limits of the sample used.

One of a pair of specimens was served for the oedometer test throughout which the temperature was held constant at the controlled room temperature of 17°C or 20°C while the other for the special test in which the temperature was varied. The former kind of test will be called LT test and the latter HT test hereafter. A specimen is specified by the batch number and the kind of the test; for example, the specimen "1-HT" means the specimen that was prepared from the No.1 batch and served for the HT test.

Table 1: Descriptions of specimens, loading procedures and corresponding temperature conditions.

Series No.(1)	Initial Water Content w_i(%)	Vertical Pressure(2) p (kPa)					Temperature(3) T(°C)
		p_1	p_2	p_3	p_4	p_5	
1	59.3	160	10	1280	-	-	17/75
2	69.4	160	10	1280	-	-	17/75
3	80.8	160	10	1280	-	-	20/75
4	108.9	160	40	930	250	1810	20/75

Notes: (1)For each series, two specimens were tested: one for the HT tests and the other for the LT test.

(2)Virgin loading: $p=0 \to p_1$
Unloading: $p_1 \to p_2$
Reloading: $p_2 \to p_3$
2nd Unloading: $p_3 \to p_4$
2nd Reloading: $p_4 \to p_5$

(3)The higher temperature was applied in the HT tests; the lower temperature is the controlled room temperature when each series of tests were carried out.

2.3 Testing procedures

Loading procedures and corresponding temperature conditions are shown in Table 1.

(a) loading procedures

Every specimen was first loaded incrementally to the pressure $p=p_1$, then unloaded to p_2. After the completion of the rebound at p_2, they were reloaded to p_3. Only two specimens of the series No.4, 4-HT and 4-LT, were again unloaded from p_3 to p_4 and reloaded from p_4 to p_5.

For both kinds of tests, HT and LT, on the series No.1 to 3, the load increment ratio ($\Delta p/p$) and the loading period were made in accordance with the standard method for one-dimensional consolidation tests (JIS A 1217-1980): $\Delta p/p$ was 1 and the period of time for each load was 1 day. This period was sufficient for the primary consolidation to be completed. For the unloading, $\Delta p/p$ was different between the series.

For the series No.4, $\Delta p/p$ was changed from 1 in the virgin loading to

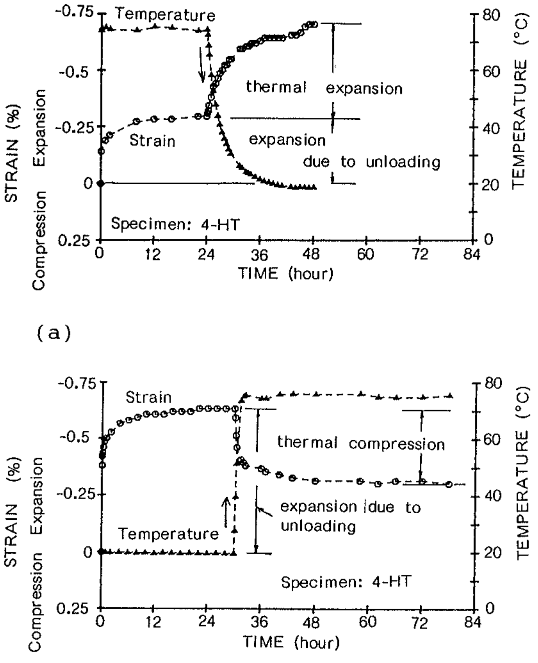
0.25 in the first and second reloadings in order to examine the detail of the behavior under the pressure near the consolidation yield stress. The loading period was also changed in the first and second reloadings for the time saving: once the primary consolidation ended at each stage, a subsequent load increment was applied. The secondary compression could not be observed except in the virgin loading therefore.

(b) temperature condition

For the specimens, 1-, 2- and 3-HT, the temperature was held at 75°C in the virgin loading and subsequent unloading; and it was lowered to the room temperature after the completion of the rebound at $p=p_2$. After the change in the vertical strain at $p=p_2$ completely ceased, the reloading was started. The total period of time for the swelling at $p=p_2$ was four days.

For the specimen 4-HT, the testing procedure applied in the virgin loading and unloading is the same as that described above except that the total period of time for the swelling at $p=p_2$ was two days; after the rebound due to the second unloading from $p=p_3$ to p_4, the temperature was again raised to 75°C at $p=p_4$ and then the second reloading was done.

For the LT test specimens, the temperature was held constant at the controlled room temperature throughout tests. The period in every loading stage was made identical to that for the HT test specimen in the same series.



(a)

(b)

Fig.3: Variations of the vertical strain and temperature with time for the specimen 4-HT: (a)decrease in temperature at p=40kPa; and (b)increase in temperature at p=250kPa.

3. RESULTS

3.1 Volume change due to change in temperature

In the HT tests, the temperature was allowed to gradually decrease to the room temperature when the rebound due to the removal of load was completed at $p=p_2$. For the specimen 4-HT, the temperature was raised also at $p=p_4$, i.e., after the second unloading.

The strain behavior at $p=p_2$ and

p=p_4 is as in the following (see Fig.3(a) and (b)):

1)expansive strain occurred by the removal of load and it continued to develop by the subsequent decrease in temperature, whereas the strain changed to compressive from expansive when the temperature was raised; and 2)the change in the strain was nearly proportional to the change in temperature. Furthermore, the rate of the change in strain to the change in temperature was almost identical for both cases of decrease and increase in temperature.

The first observation agrees with the results reported in a number of researches (e.g. Mitchell,1976). The second one implies that the strain caused by the change in temperature would be recoverable. However, the strain will not always be recoverable but will depend on the condition of temperature applied (Mitchell,1976).

3.2 Effects of temperature on compressibility

The e-log p curves obtained from the series No.1 and No.4 are shown in Fig.4(a) and (b), respectively. These two series have been chosen here to take into account the effects of the water content. In fact the series No.1 was carried out at the lowest water content and No.4 at the highest one. In the inserted figure in Fig.4(a), the behavior when the normal consolidation was again attained in the reloading is emphasized.

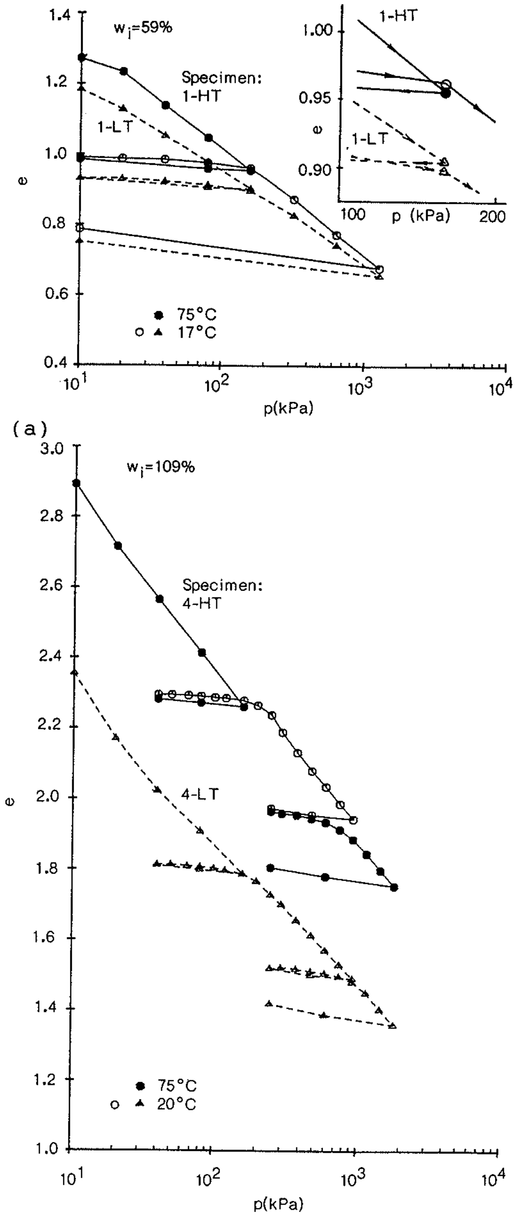


Fig.4: e-log p relations: (a) for the specimens of the series No.1; and (b) for the specimens of the series No.4.

(a) compression index in the normal consolidation

The compression index, C_c, can be obtained from the e-log p curves. The index in the normally consolidated states is compared between HT and LT tests in Fig.5.

In the virgin loading (and the second reloading of the No.4), in which the temperature was higher in the HT tests than the LT tests; and we can say that C_c can be larger with higher temperature. This observation is in agreement with the results by Plum and Esrig (1969).

In the normally consolidated state that was again reached in the reloading , C_c is larger for the HT tests than for the LT tests. This indicates that C_c becomes larger with the high-temperature history than without it.

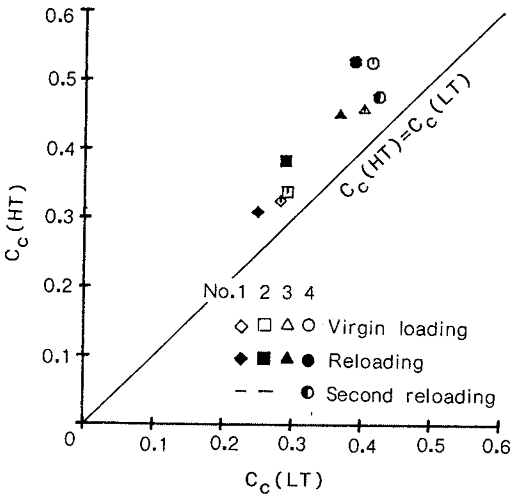


Fig.5: Comparison of compression index in the normal consolidation state between HT and LT tests

(b) consolidation yield stress

Referring to Fig.4(a), in the HT tests, void ratio at $p=p_1$ in the reloading is higher than that in the virgin loading, but not in the LT tests. The magnitude of the rebound caused by the lowering of temperature at $p=p_2$ could not be recovered by the subsequent reloading at the lowered temperature. This suggests us that compressibility would be a function of two variables of temperature and vertical stress, and that the state of specimen could be elastic for the range of temperature less than the maximum temperature having been given in the past even if the stress becomes larger by some magnitude than the preconsolidation stress, p_1.

Referring to Fig.4(b), we can see that the consolidation yield stress is larger than p_1 in the reloading whereas it is less than p_3 in the second reloading; we note here that p_1 and p_3 are the maximum preconsolidation stress for the reloading and second reloading, respectively. This behavior is similar to that of aged normally consolidated clays, on which the apparent preconsolidation behavior or p_c-effect is observed (Bjerrum, 1967).

We recall that, for the series No.4, the load increment ratio ($\Delta p/p$) was decreased to 0.25 in the reloading; the effect of the decrease in the ratio may be reflected in the behavior. However, such an effect must be included in both behaviors of specimens 4-LT and 4-HT, and therefore the p_c-

effect mentioned above can be considered as the effect of the high-temperature history.

3.3 Effects of temperature on the rate of secondary compression

Effects of temperature on the rate of secondary compression were examined. An example of the results is shown in Fig.6. The effects of temperature on the rate of secondary compression could be seen at the low level of p in the virgin loading stage; this was clear, especially, for specimens with higher initial water content.

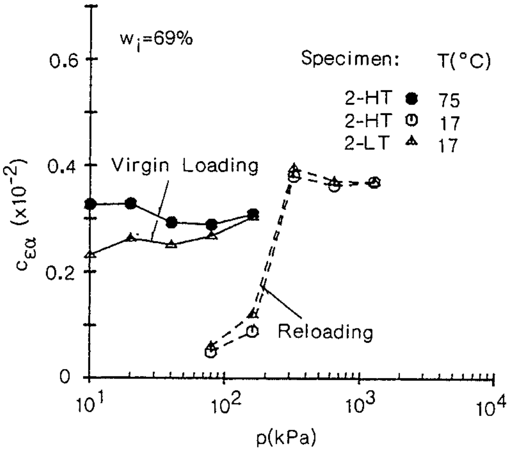


Fig.6: An example of the relationship between the rate of secondary compression $c_{\varepsilon\alpha}$ and the pressure p, where $c_{\varepsilon\alpha}$ is defined as $d\varepsilon$/dlog(time).

3.4 Effects of temperature on the rate of primary consolidation

In Figs.7(a) to (d), the coefficient of primary consolidation c_v' is plotted against the average pressure $\bar{p}$, where c_v' was determined on the basis of the vertical displacement that occurred in the primary consolidation (JSSMFE, 1979).

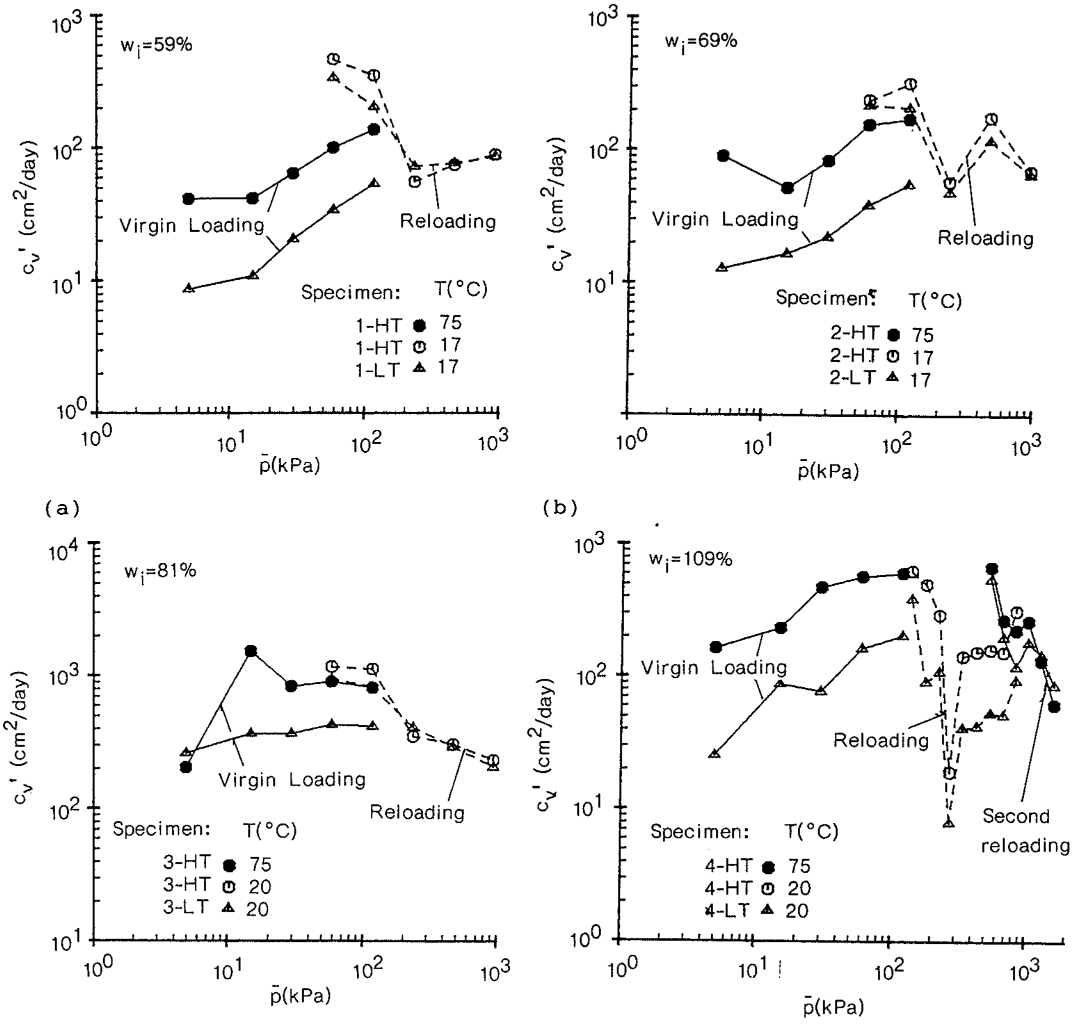
To determine the coefficient, the $\sqrt{t}$ method was applied. The time interval for the reading of the vertical displacement was made in accordance with the standard method in JSSMFE(1979) for the series No.1, 2 and 4; by the method, the coefficient of consolidation could not be determined definitely in some cases, especially in the over-consolidated state. To make the determination of c_v' more definite, the time interval of 0.1 sec was adopted for the series No.3, which was carried out last. The coefficient was more definitely determined in the series No.3 than in other series thereby.

Figs.7(a) to (d) show that:

1)In the virgin loading of all series, larger values for c_v' are obtained in the HT tests than the LT ones; in this loading stage, the temperature was different between these kinds of tests.

2)However, in the second reloading stage of No.4, in which the temperature was also different between HT and LT tests as in the virgin loading, there is almost no difference in c_v' between LT and HT tests.

3)In the reloading stage of all series, where the temperature was not dif-



(c) (d)

Fig.7 Relationships between the coefficient of primary consolidation, c_v', and average consolidation pressure, $\bar{p}$: (a)series No.1; (b) No.2; (c) No.3; and (d) No.4.

ferent between specimens of HT and LT tests, nearly the same values for c_v' are obtained, at any pressure, between two specimens in the same series.

From these findings, we can conclude that c_v' tends to be larger by the virgin heating, but not by the second heating.

4. DISCUSSION

It was shown in the preceding section that c_v' can be higher at the high temperature than at the low temperature at a given value for p. The ratio $c_v'(T)/c_v'(T')$ can be up to nearly 7 (see Figs.7(a) to (d)) when the temperature T is higher than T' by more than 50°C. In this section we try to examine a possible cause of such temperature dependence of c_v'. To do so, the Terzaghi's theory of consolidation and the modified Kozeny-Carman equation for permeability (Taylor,1948) will be applied.

The coefficient of primary consolidation c_v' is defined in the Terzaghi's theory of consolidation as

$$c_v'(T) = \frac{k(T)}{m_v(T)\,\rho_w(T)g} \qquad \text{----------(1)}$$

where k is the coefficient of permeability, m_v the coefficient of volume change, ρ_w the mass density of water, and g the acceleration of gravity. The notation x(T) denotes the value for a quantity x at the temperature of T.

The ratio of c_v' at temperature T to c_v' at T'(<T), at a given value of p, can be expressed, from Eq.(1), as

$$\frac{c_v'(T)}{c_v'(T')} = \frac{r_k}{r_{mv}\cdot r_{\rho w}} \qquad \text{----------(2)}$$

where

$$r_k = \frac{k(T)}{k(T')},\quad r_{mv} = \frac{m_v(T)}{m_v(T')} \text{ and } r_{\rho w} = \frac{\rho_w(T)}{\rho_w(T')}$$

Eq.(2) indicates that the ratio of c_v' depends mainly on the temperature dependence of m_v and k, because ρ_w only slightly depends on the temperature. The temperature dependence of m_v can be evaluated from such results as those shown in Fig.4, whereas that of k can not be directly evaluated from the experimental results shown so far.

Permeability of saturated soils is a function of properties of the pore water and properties of the soil skeleton. No comprehensive theory other than the Kozeny-Carman equation seems to have been developed in which these properties can be taken into account. The equation was simplified for soils by Taylor(1948) as follows:

$$k(T) = C \frac{\rho_w(T)}{\eta(T)} \frac{e^3(T)}{1+e(T)} g.D_s^2 \qquad \text{----------(3)}$$

where D_s is a representative diameter of soil grains, η is the viscosity of pore fluid, and C is a factor introduced and called 'composite shape factor' by Taylor(1948).

The factor expresses the shape effects of cross sections of flow channels as well as the shape effects of soil grains. The factor may depend on the temperature, and it is temporarily considered to be a function of T. We will assume later, with some reasons, that the factor does not depend on the temperature.

Eq.(3) results in the ratio of permeability at the temperature T to that at T' as follows:

$$r_k = \alpha \frac{r_{\rho w} \cdot r_e}{r_\eta} \qquad \text{----------(4)}$$

where

$$\alpha = \frac{C(T)}{C(T')}, \; r_\eta = \frac{\eta(T)}{\eta(T')} \quad \text{and} \quad r_e = \frac{e^3(T)}{1+e(T)} \Big/ \frac{e^3(T')}{1+e(T')}$$

By inserting Eq.(4) into Eq.(2), we can obtain the following relation:

$$\frac{c_v'(T)}{c_v'(T')} = \alpha .f \qquad \text{----------(5)}$$

where

$$f = \frac{r_e}{r_\eta \cdot r_{mv}}$$

Eq.(5) gives the theoretical equation for the ratio of c_v'. This equation has been derived by temporarily considering that the composite shape factor depends on the temperature. However, here, we assume that the composite shape factor is not a function of the temperature. This assumption would be justified by considering the followings:

1)the change in the shape of flow channels due to the change in temperature will always be followed by the change in void ratio; and therefore

2)the temperature dependence of the shape factor can be taken into account by evaluating the temperature dependence of the void ratio.

With this assumption, the term f gives a theoretical ratio of c_v'. We can evaluate all the factors in f by using the relationships of m_v and e to p, which were obtained from HT and LT tests for all the series. As for the data on the viscosity of water, we can refer to literature.

In Figs.8(a) and (b), f evaluated in the way mentioned above is plotted against the ratio of c_v' obtained from each pair of specimens of the same initial water content. The coefficients of primary consolidation in the HT tests and in the LT tests are denoted by $c_v'(HT)$ and $c_v'(LT)$, respectively. In Fig.8(a), the results in the virgin loading (and also in the second reloading for the series No.4) are shown; in these loading stages, the temperature was made different between the HT and LT tests. Fig.8(b) shows the results in the reloading stage, in which the temperature was made identical between the HT and LT tests.

We can see in Fig.8(a) that:

1)The correlation between the experimental ratio and the theoretical one, f, is better for the series No.2 and 3 than for No.1 and 4, of which the plots rather scatter.

2)In spite of such scatter, the values of f are larger than unity for all cases, which indicates that the theories adopted here can explain an aspect of the temperature dependence of c_v', i.e. c_v' can be higher at the high temperature than at the lower temperature.

3)However, the theories can not explain the behavior after the second heating on c_v' because, in the second reloading of No.4, f is much larger than the theoretical ratio.

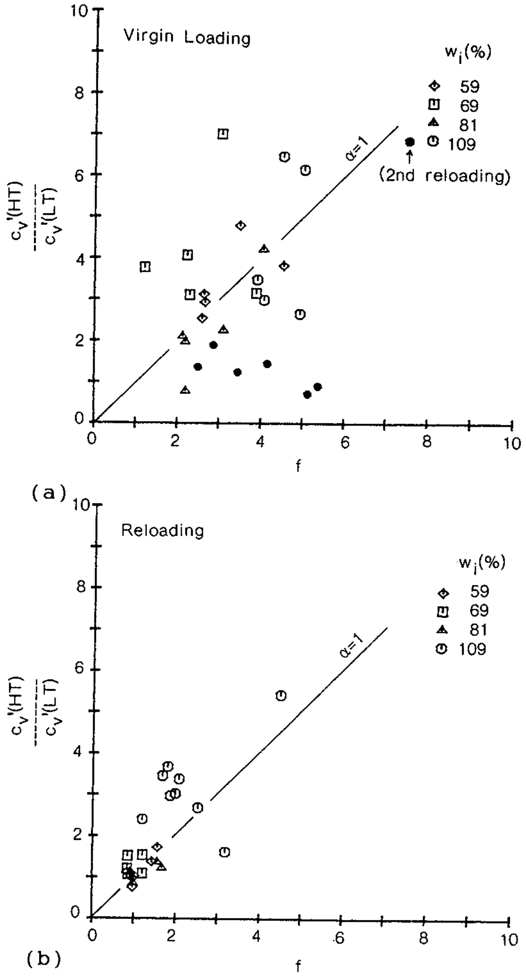


Fig.8: Relationships between the measured ratio of c_v', $c_v'(HT)/c_v'(LT)$, and the theoretically predicted ratio, f: (a)in the virgin loading (and the second reloading for the series No.4.); and (b)in the reloading.

It is in the case of No.3 (w_i=81%) that the measured ratio best agrees with the theoretical one. This seems to have resulted from that c_v' was determined more definitely than for other cases.

Furthermore it can be seen in the figure that the relation between f and the measured ratio of c_v' may be independent of the initial water content.

In Fig.8(b) we can see a better correlation between f and the measured ratio of c_v' than in Fig.8(a). However, for the series No.4, both f and the measured ratio are much larger than unity; this may imply that some effects of the first heating in the virgin loading on c_v' remains in the reloading.

5. CONCLUSIONS

Two kinds of oedometer tests were carried out: one is the tests in which the virgin loading and subsequent unloading were made at the temperature of 75°C and the reloading at the room temperature; and in the other the temperature was held constant at the room temperature.

The effects of the high temperature and the high-temperature history on the compressibility and consolidation behavior were shown. The followings were found:
1)larger values for C_c were obtained by consolidating at such a high temperature as 75°C. The values for C_c of specimens subjected to the high-temperature history were also larger than those without the history;
2)the effects of temperature on the rate of secondary compression was observed only at the low level of p, in particular, for the specimens of high initial water content; and
3)larger values for c_v' were obtained when consolidated at the high temperature; however c_v' was not different under the same temperature between specimens subjected or not to the high-temperature history.

The reason why c_v' can differ under different temperatures was discussed by applying the Terzaghi's theory of consolidation and the Taylor's equation for coefficient of permeability. It was shown that:
4)the theories adopted here can explain that c_v' tends to increase with the increase in temperature.

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