One-dimensional compressive behaviour of reconstituted clays under high temperature and small strain rate

Comportement oedométrique des argiles reconstituées sous fortes température et à faible vitesse de déformation

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ABSTRACT: It is considered that a long term settlement of clay deposits so called secondary consolidation is caused by clay viscosity. In this paper, the viscous property of clayey soils is examined from two viewpoints of temperature and strain rate effects. To investigate these effects, constant rate of strain (CRS) loading test, in which the strain rate is changed during the test, was carried out at a temperature of 10℃ and 50℃for reconstituted Louiseville clay samples. It is found that as temperature is higher and the strain rate is smaller, the clay specimen does not follow conventional viscous behaviour, for example, the Isotache model, but the gradient of stress-strain curve considerably decreases. The reason for different behaviour from the Isotachemodel may be considered to be attributed to creation of a new structure to resist the external deformation, under high temperature and slow strain rate conditions.

RÉSUMÉ : On considère que le tassement à long terme de dépôts d'argile, appelé consolidation secondaire, est causé par la viscosité es argiles. Dans cette étude, on examine le comportement visqueux des sols argileux de deux points de vue : celui des effets de la température et celui des effets de la vitesse de déformation. Afin d'étudier ces effets, on a réalisé sur des échantillons d'argile de Louiseville reconstitués à des température de 10°C et 50°C un essai oedométrique avec une vitesse de déformation constante (CRS/Constant Rate of Strain), dans lequel la vitesse de déformation est modifiée durant l'essai. On a constaté que lorsque la température est plus élevée et la vitesse de déformation plus faible, l'échantillon d'argile ne suit pas le comportement visqueux conventionnel, par exemple le modèle Isotache, mais que la pente de la courbe de contrainte-déformation plastique diminue considérablement. On peut considérer que la raison de la différence de comportement par rapport au modèle Isotache doit être attribuée à la création d'une nouvelle structure pour résister aux déformations externes.

KEYWORDS:clay, one-dimensional consolidation, strain rate effect, temperature effect.

1 INTRODUCTION

In one-dimensional consolidation, the stress-strain relationships of clayey soils exhibit various viscous behaviours. One of them is well known behaviour depending on strain rate. It was reported that the stress-starin relationships of clayey soils were determined by strain rate (for example, Leroueil et al., 1985; Tanaka, 2005), and such strain rate effectwas simply described by Isotache model (Šuklje, 1957).On the other hand, the other viscous effect related to temperature is also observed. For example, Eriksson(1989)reported that the consolidation yield stress (p'_c) decreases with an increase in temperature as shown in Fig.1. These viscous effects, caused by strain rate and temperature, on stress-strain relationships of clayey soils arevery similar to each other, and they have been already reserached in previous studies.However, most of them focused on either one of the viscous effects: strain rate effect and temperature effectindividually, not simultaneously.

In this study, combined effects of strain rate and temperature on consolidation properties of clayey soils are examined. Especially, temperature effect on compressibility under smallstrain rate, which is observed in the field, is in detail discussed.

2 TESTING METHOD AND SAMPLES

In order to investigate combined effects of strain rate and temperature on consolidationproperties of clayey soils, a special constant rate of strain (CRS) loading test, in which the strain rate is changed during the test, was carried out at different temperatures.To observe the temperature effect, it is preferable to carry out CRS test using the same specimen, i.e., by changing the temperature during the testing, to avoid any differences in soil properties for different specimens. However, changing the temperature during the testing is very difficult in practice. When the temperature is changed, the measuring system as well as the specimen itself is influenced. One example is the zero drift of the sensors.For this reason, the CRS tests were carried out at two constant temperatures: 50℃and 10℃.

Figure 2 shows a schematic view of the CRS testing apparatus used in this study.The CRS apparatus followed JIS (Japanese Industrial Standard) A 1227 (2009): the specimen was 60 mm in diameter and 20 mm in initial height.The bottom of the specimen was connected to a transducer to measure the water pressure. The applied load was measured by a load cell at the bottom of the consolidation cell. A back pressure of 100 kPa was applied to assure good saturation of the specimen during the test. The effective vertical pressure (p') was calculated assuming that the excess pore water pressure in the specimen is distributed in a parabolic manner as expressed by Eq. (1):

$$p' = \sigma - \frac{2}{3}\Delta u \qquad (1)$$

where, σ is the total pressure on the specimen and Δu is the excess pore water pressure.

A loading apparatus consisted of a Step Motor System whose resolution is as accurate as 2,621,440 pulses per revolution, and this was controlled by a personal computer (see Tsutsumi and Tanaka, 2011).The displacement was not measured by a conventional dial gauge, but obtained directly by counting the number of revolutions of the step motor and corrected by the deformation of the apparatus system. The nominal strain (ε^{T}), the void ratio (e) and the nominal strain rate ($\dot{\varepsilon}^{T}$)werecalculated using the displacement.

As shown in Fig. 2 a metal pipe was spiralled around the specimenand an isothermal liquid was circulated through this pipe to control the temperature(T), which was measured by a thermocouple attached to the upper side of the consolidation cell.To avoid the offset drift of measuring instruments due to changes in the temperature, the whole CRS testing apparatus was preliminarily kept under a testing temperature by circulating isothermal liquid.Then, the measuring instruments were initialized and the CRS test was started.

Reconstituted samples were used, to avoid the variability in soil properties for tested samples and to identify only the temperature effect. The samples were made from Louiseville clay, which was obtained from the Louiseville site along the St. Lawrence River in Quebec, Canada. Their main geotechnical properties are as follows: the liquid limit,the plastic limit and the density of soil particles are 71%, 22% and 2.767g/cm^3, respectively. Its detailed properties were referred by Tanaka et al. (2001).

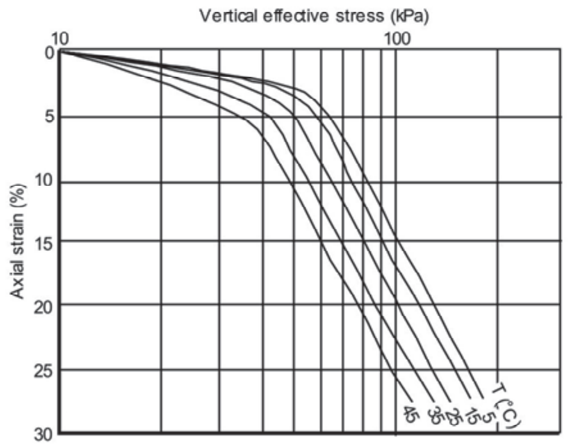

Figure1. A typical example of temperature effect on compression curves (after Eriksson, 1989).

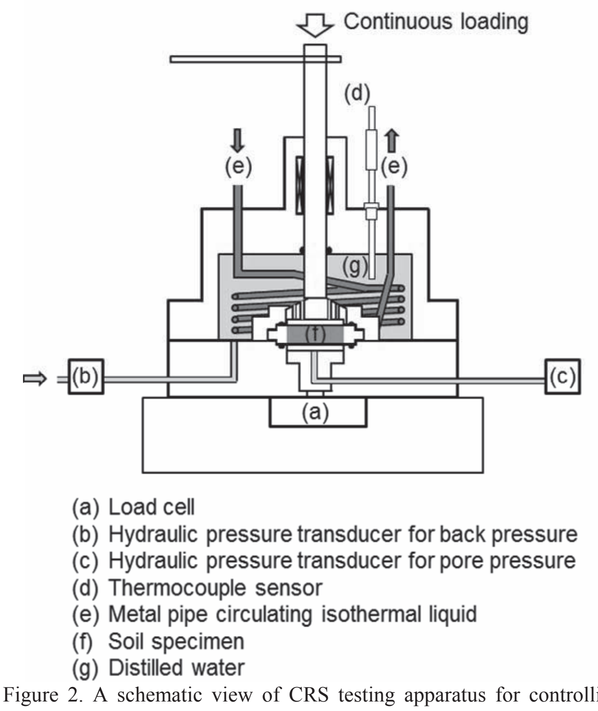

Figure 2. A schematic view of CRS testing apparatus for controlling temperature.

3 TEST RESULTS AND DISCUSSIONS

3.1 *Temperature effects on permeability*

Figure 3 shows therelationshipbetween$e$-log $p'$and Δu-log p'obtained from the CRS tests for Louiseville reconstituted samples. The testing was performed at a constant T value of 10 ℃ or 50 ℃, while the strain rate was changed during a test. The e-log p' curve segments between Points a and b as well as d and f were obtained under the reference strain rate of 3×10^{-6} s^{-1} ($\dot{\varepsilon}^{T}$) and that between Points b and d under $\dot{\varepsilon}^{T}$/100. In Fig.3,Δu generated at 50℃ is clearly smaller than that at 10℃. It is considered that such a difference in Δu is caused by different hydraulic conductivity (k). According to JIS A 1227 (2009), k may be calculated by Eq. (2):

$$k = \frac{\rho_{wT} g_n \dot{\varepsilon}^{T} H_0 H_t}{2\Delta u} \quad (2)$$

where, ρ_w, g_n, H_0 and H_t are the unit weigh of water, the acceleration of gravity, specimen heights at initial and at each moment (t), respectively. The relationships of e-log k are shown in Fig. 4, where the k values were indicated at only normally consolidated (NC) states and they were not calculated in the phase “b-d”, because the strain rate was so small that the value of Δu was nearly zero andcould not be measured with sufficient accuracy. When k at 50℃ and 10℃ is denoted respectively as k_{50} and k_{10}, k_{50} is larger than k_{10} and the e-log k relationships for k_{50} and k_{10} are parallel to each other, as shown in the figure.This means that the ratio of k_{50}/k_{10} is constant at the same e value.

It is well known that the viscosity of water is strongly influenced by temperature. Indeed, in the testing method of permeability defined by JIS A 1218 (2009), the measured k value is calculated at 15℃ (k_{15}), taking account of the change in the water viscosity due to temperature. The ratio of k_{50}/k_{10} is represented by Eq. (3) with the viscosity coefficient of pure water (η_T).

$$\frac{k_{50}}{k_{10}} = \frac{\eta_{10}}{\eta_{50}} \quad (3)$$

The ratio η_{10}/η_{50} is calculated to be 2.39 based on η_T of pure water given in the Chronological Scientific Table (2004). As shown in Fig. 4, the ratio of k_{50}/k_{10} for Louiseville clay is 2.44, which is very close to the ratio η_{10}/η_{50}. Therefore, it may be concluded that the changes in k and Δu with T are caused by those of the water viscosity.

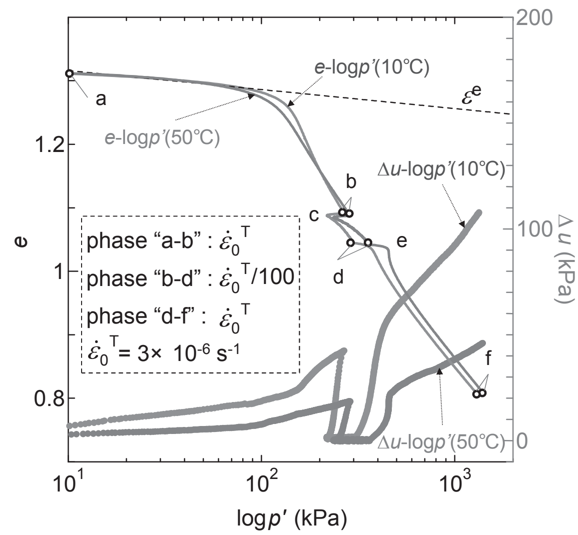

Figure 3. The e-log p'relationships obtained from CRS tests.

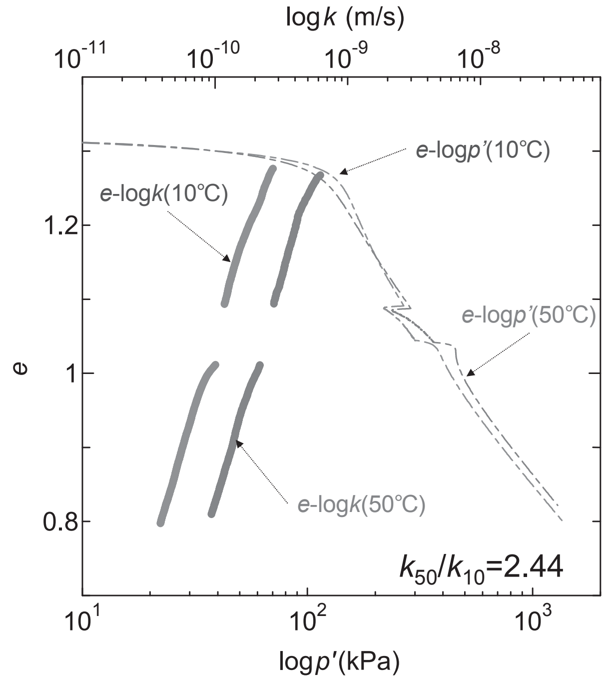

Figure 4. The variance of hydraulic conductivity with void ratio.

3.2 *Combined effects of strain rate and temperature on compressibility*

The temperature effect on compressibility beforedecreasing $\dot{\varepsilon}^{T}$ is examined by comparing the *e*-log *p'* curves in the phase of"a-b" at 10℃ and 50℃, as shown in Fig. 3. It is observed that the *e*-log *p'* relationship at high temperature shifts to the left side: i.e.,p'_c decreases with an increase in *T*.In addition to the decrease in the p'_c value due to high temperature, it can be recognized that the*e*-log *p'* curve at 50℃ crosses the curve at 10 ℃: the gradient of *e*-log *p'* relationship at the normally consolidated state (C_c)under the high temperature is smaller than that at low temperature. This behaviour is completely different from that presented in Fig. 1.

At Pointb in Fig. 3, a strain rate was instantly decreased during the tests.It is considered that the strain rate effectis relevant only to the viscous component of sample deformation.For example, in the Isotache model, the total strain (ε^{T}) is assumed to consist of the elastic strain (ε^{e}) and the visco-plastic strain (ε^{vp}) indicated in Eq. (4):

$$\varepsilon^{vp} = \varepsilon^{T} - \varepsilon^{e} \tag{4}$$

To evaluatethe strain rate effect on compressibility, *e*-log *p'* relationships are rearranged as the relationships between ε^{vp} and *p'*.It is assumed, in this study, that elastic strain is independent of temperature, andincremental ε^{e} is calculated using the slope of *e*-log *p'* relationships before reaching p'_cas shown in Fig. 3, where the *e*-log *p'* relationships for 10 and 50℃ are nearly identical.The relationships between ε^{vp} and *p'* are shown in Fig. 5, where the *p'* is normalized by the effective stress at Point b(p'_1), just before the strain rate is decreased.And the vertical axis indicates the incremental ε^{vp} from ε^{vp}at Point b ($\Delta\varepsilon^{vp}$). Here, the reference equi-strain rate line ($ESRL_0^{vp}$), which is presented by broken lines in the figure, is defined asε^{vp}-log *p'*relationship that a specimen may follow if visco-plastic strain rate ($\dot{\varepsilon}^{vp}$) is not changed. Tsutsumi and Tanaka (2011) assumed that the $ESRL_0^{vp}$ can be expressed by a cubic function and the constants in the equation were obtained by the least square fitting.

The first interesting finding from Fig. 5 is that for both temperatures, *p'* decreases with a decrease in the strain rate due to the viscous effect, and this decrease in terms of the ratio p'/p'_1 is not significantly influenced by *T*.After p'/p'_1 attained the minimum value,the $\Delta\varepsilon^{vp}$-log (p'/p'_1)relationship seen in Fig. 5is strongly influenced by temperature.In the phase of "c-d", where the strain rate becomes constant at $\dot{\varepsilon}_0^{vp}$/100,the $\Delta\varepsilon^{vp}$-log (p'/p'_1)curve at 50℃ approachesand crossesthe $ESRL_0^{vp}$. In the phase of "d-e-f", where the strain rate returned to the original rateof $\dot{\varepsilon}_0^{vp}$, the curve considerably overshoots the $ESRL_0^{vp}$.On the other hand, the $\Delta\varepsilon^{vp}$-log (p'/p'_1)curvein the phase of "c-d" at 10 ℃ does not cross the $ESRL_0^{vp}$ and the amount of the overshootdue to returning the original strain rate is considerably smaller than that at 50℃.Figure 6 shows a changein the gradient of $\Delta\varepsilon^{vp}$-log (p'/p'_1)curve with increasing$\Delta\varepsilon^{vp}$ in the phase of "d-e-f". In the Fig. 6, thegradient of $\Delta\varepsilon^{vp}$-log (p'/p'_1)curve at 50℃ increases sharply at Point d, and then it decreases drastically after Point b. Such a drastic change of compressibility is often observed in the compression curves around p'_c of thestructured clays.

It can be considered that the specimen at high temperature and very small strain rate has gained the ability to resist the external deformation, as if the specimen has developed new structure. A similar phenomenon is observed even under the relatively fast strain rate. That is, as alreadymentioned in the phase of"a-b",C_c at 50℃ is slightly smaller than that at 10℃, although this difference is not significant. This tendency is more prominent under the extremely small strain rate of $\dot{\varepsilon}_0^{vp}$/100.

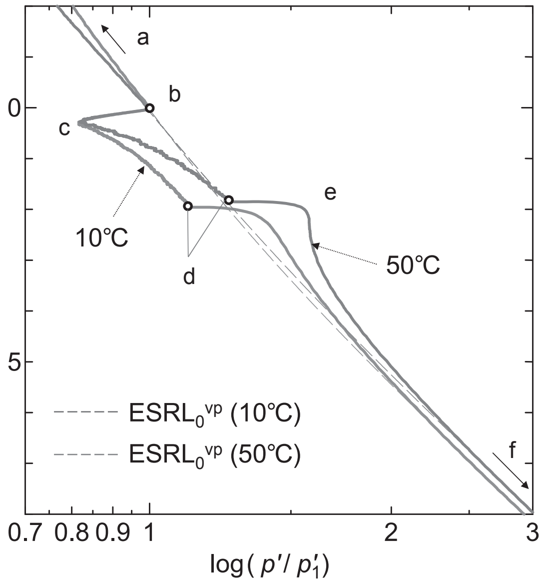

Figure5. The relationship between incremental visco-plastic strain and normalized effective stress.

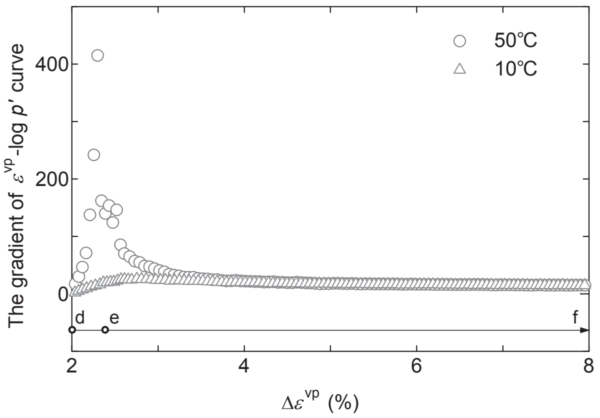

Figure 6. A change in the gradient of ε^{vp}-log (p'/p'_1)curve with increasing $\Delta\varepsilon^{vp}$ at the phase of "d-e-f".

3.3 *Discussions*

Two important effects on compressibility caused by the changing temperature were identified in this study. One is the so-called viscous behaviour due to high temperature conditions observed in the phase of "a-b" in Fig. 3: that is, p'_c decreases with an increase in *T*. Another effect is the gaining of the ability to resist deformation, i.e., decreasing C_c with an increase in *T*. This effect becomes much more prominent when the strain rate is smaller, as observed in the phase of "c-d" under $\dot{\varepsilon}_0^{vp}/100$ in Fig. 5; normalized *p'* at given $\Delta\varepsilon^{vp}$ is larger for higher *T*. As a result, in the phase of "d-e-f" in Fig. 5, the $\Delta\varepsilon^{vp}$-log (p'/p'_1) curve at 50℃ considerably overshoots the corresponding $ESRL_0^{vp}$, as if the clay specimen experienced ageing in the previous phase of "c-d". However, this overshoot is destructed by the faster loading under $\dot{\varepsilon}_0^{vp}$ and the $\Delta\varepsilon^{vp}$-log (p'/p'_1) curves return to their original trend.

According to Tsuchida et al. (1991), an increase in temperature provides the same effect as ageing on clay samples. They mentioned that this ageing is caused by cementation and this cementation is accelerated by an increase in temperature. A similar ageing effect was also reported byTowhata et al. (1993). In Fig. 7, cited from Towhata et al. (1993), clay samples were subjected by incremental step loadings after applying a load of 160kPa at 90℃ for various durations of time. The *e*-log *p'* relationship for heated samples shifts to higher *p'* in comparison to the reference relationship obtained by the end of primary consolidation indicated by the dotted line. They considered that such an ageing effect was caused by the acceleration of secondary consolidation: i.e., clay particles are closely rearranged because an increase in temperature reduces the viscosity of the adsorbed water layer on the surface of soil particles. As a result, the specimen develops a new structure, exhibiting higher stiffness against subsequent loading. It may be also considered that some types of structure are created during the loading process in the CRS test and its creation is considerably accelerated under high temperature conditions.

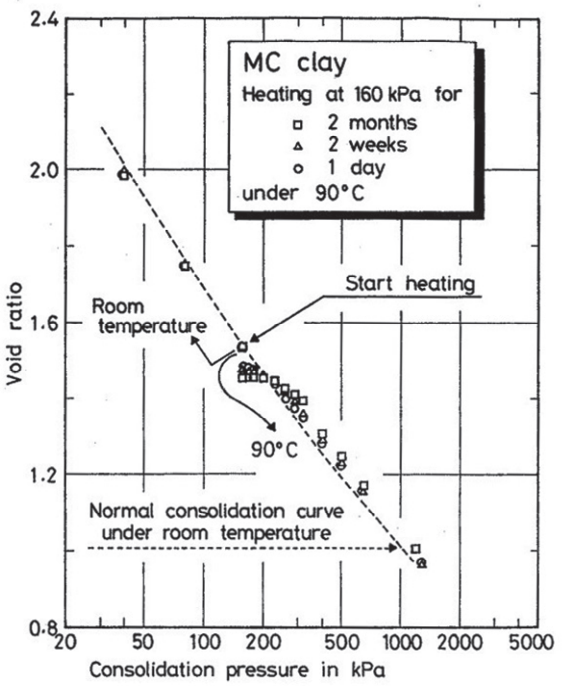

Figure 7. Thermal aging behaviour obtained from incremental loading consolidation test after Towhata et al. (1993).

4 CONCLUSIONS

To examine the combined effects of temperature and strain rates on the consolidation properties of clay, a series of CRS tests, in which the strain rate was not constant but changed during the test, was carried out at temperatures of 10℃ and 50℃for reconstitutedLouisevilleclay samples. The following conclusions were drawn:

1) The hydraulic conductivitywas strongly dependent on temperature. The reason for this is that the water viscosity increases with a decrease in temperature. As a result, the excess pore water pressure generated in the specimen at 10℃ was much higher than that at 50℃.
2) The yield effective stress decreased with increasing temperature, indicating that the clay specimens exhibited viscous behaviour by heating. However, such a viscous effect disappeared with a decrease in the void ratio (*e*) during a subsequent loading: under the higher level of the effective stress (*p'*). That is, the slope of the *e*-log *p'* curve at 50℃ at the normally consolidated state (C_c) was smaller than that at 10℃.
3) The tendency of a decrease in C_c, i.e., lowering compressibility, was more prominent under the loading condition of small strain rate.The reason for a decrease inC_c under high temperature at small strain rate may be attributed to the structure created.This explanation may be applied to the observed phenomenon of overshooting the *e*-log *p'*, when the strain rate was increased.

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