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SOME OBSERVATIONS ON THE OEDOMETRIC CONSOLIDATION STRAIN RATE BEHAVIORS OF SATURATED CLAY

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ABSTRACT

Data obtained from laboratory incremental loading (IL) oedometer tests are evaluated to study the consolidation strain rate behaviors of saturated clay. Soil consolidation is a time-dependent volume change (compression) process induced by both dissipation of excess pore water pressure and reorientation of mineral grains. As most consolidation test setups are not equipped with pore water pressure transducers, the process of consolidation is most frequently monitored by measuring specimen compression and consolidation time during both primary consolidation and secondary compression. Strain rate values can readily be computed from data of specimen compression at different times of consolidation. Of particular interest is the relationship between end-of-primary strain rate and consolidation pressure, since this information provides some insights on the issue of strain rate selection in the constant rate of strain (CRS) consolidation test. The CRS consolidation test is usually carried out using a strain rate reasonably higher than the end-of-primary strain rate, so that only small excess pore water pressure is developed at the bottom of specimen. Information on the range of strain rates during primary consolidation is beneficial for assessing the CRS test for studying the strain rate effect on the compressibility of clays. Effects of sample disturbance, stress history, load increment ratio, and consolidation on the end-of-primary strain rate are evaluated by comparing end-of-primary strain rates of undisturbed and disturbed samples, and at normally-consolidated and overconsolidated conditions.

Key words: Strain rate, laboratory test, consolidation, clay.

1. INTRODUCTION

For the prediction of settlement of structures on compressible soils, both constant rate of strain (CRS) and incremental loading (IL) oedometric consolidation tests have been used to determine the e-log σ'_v relationship and therefore the preconsolidation pressure. A still unresolved question as to how does time or strain rate affect clay compressibility has been widely studied both in the laboratory and in the field (*e.g.*, Bjerrum 1967; Sallfors 1975; Ladd *et al*. 1977; Jamiolkowski *et al*. 1985; Leroueil *et al*. 1985; Mesri and Choi 1985; Crawford 1988; Degago *et al*. 2009; Mesri and Feng 2009). Although the CRS test provides a means to determine clay compressibility with different strain rates, it does not address the problem of clay consolidation resulting from excess pore water pressure dissipation. The CRS test produces a large number of stress and strain data so that the e-log σ'_v relationship is better defined. Generally, different e-log σ'_v relationships and preconsolidation pressures are obtained from CRS consolidation tests with different imposed strain rates. Therefore, a proper selection of the strain rate for CRS test is necessary (*e.g.,* ASTM D4186 1989). The selection of strain rate concerns about generating a small excess pore water pressure at the impervious boundary of the oedometric specimen, so that both the specimen is nearly uniformly consolidated and values of coefficient of consolidation are obtained. The selected strain rate is thus faster than the end-of-primary (*i.e.*, near zero excess pore water pressure) strain rate. The CRS consolidation test is seldom or never run with a strain rate smaller than the end-of-primary strain rate.

In the conventional IL oedometer test, each loading increment lasts for 24 hours so that the measured compression-time consolidation curve generally includes data of both primary consolidation and secondary compression. For example, the duration of primary consolidation may be 0.5 hour so that the duration of secondary compression would be 23.5 hours. In another extreme, the duration of primary consolidation may be 23.5 hours so that the duration of secondary compression would thus be 0.5 hour. The duration of primary consolidation is a function of compressibility, permeability, and maximum drainage distance of the specimen. A longer duration of primary consolidation usually means a smaller consolidation strain rate. It is apparent that the strain rate in IL oedometric consolidation decreases with time, but its general behavior is seldom evaluated. From the data of an IL oedometer test, different e-log σ'_v relationships may be defined, based on different consolidation times after the end of primary consolidation, *e.g.*, t_p (time of end-of-primary consolidation), $10t_p$, and $100t_p,\cdots$; or 1 day, 10 days, and 100 days, *etc*. The value of coefficient of consolidation reflects the duration of primary consolidation. The strain rate or void ratio rate is computed in numerical analysis of primary consolidation and is used to produce data of strain or void ratio change together with consolidation time as an output. In summary, laboratory data and numerical data of oedometric consolidation are rarely used to collect strain rate data. Since strain rate is a fundamental

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rheological parameter of many materials, its behavior in IL oedometric consolidation is worthy of an evaluation. Such an evaluation is also relevant to the strain rate selection considerations for CRS test.

A typical IL oedometric consolidation curve with an inflection point and a long duration of secondary compression is illustrated in Fig. 1. The slope of the portion of the curve after t_p is in many cases approximately a straight line and is commonly defined as the coefficient of secondary compression $C_{\alpha\varepsilon}$ or secondary compression index C_α. The secondary compression index C_α is a time-dependent compressibility parameter that is interrelated to the compression index C_c (*e.g.*, Terzaghi *et al*. 1996). With a known value of $C_{\alpha\varepsilon}$, the corresponding strain rate during secondary compression is computed using Eq. (1) for $t \geq t_p$:

$$\dot{\varepsilon}_\alpha = 0.434 \frac{C_{\alpha\varepsilon}}{t} \tag{1}$$

Equation (1) is derived by differentiating both sides of the definition $\Delta\varepsilon = C_{\alpha\varepsilon} \Delta\log t$ with respect to time. For $t = t_p$, Eq. (1) is rewritten as

$$\dot{\varepsilon}_{eop} = 0.434 \frac{C_{\alpha\varepsilon}}{t_p} \tag{2}$$

It should be noted that the tangent slope, denoted as $C_{t\varepsilon}$, at any time $t < t_p$ on the consolidation curve, can be used to compute the corresponding strain rate during primary consolidation with Eq. (3):

$$\dot{\varepsilon}_v = 0.434 \frac{C_{t\varepsilon}}{t} \tag{3}$$

Thus, the IL oedometric consolidation strain rate may be computed for each loading increment for consolidation times before, at, and after the end of primary consolidation.

This paper presents the results of a strain rate analysis on data obtained from four IL oedometric consolidation tests. Fundamental properties of consolidation of the clay specimens tested are presented for soil characterization purposes. The strain rates during primary consolidation and at the end-of-primary consolidation are computed. Variation of the end-of-primary strain rate with consolidation pressure is discussed with reference to the strain rate selection considerations for CRS oedeomter test. Effects of sample disturbance, stress history, load increment ratio, and consolidation pressure on the oedometric consolidation strain rate are discussed.

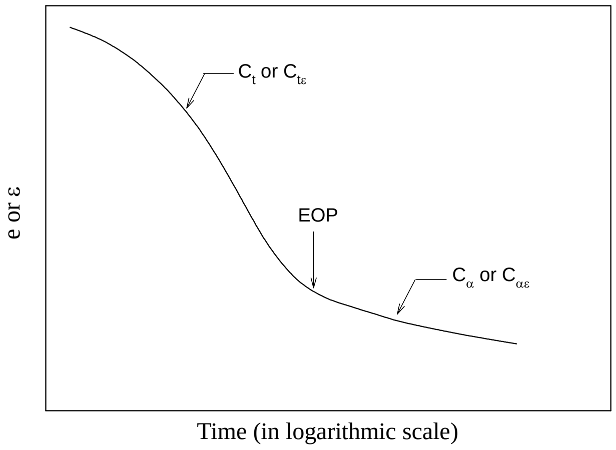

Fig. 1 Illustration of consolidation curve and definitions of time-dependent compression indexs

2. TEST PROGRAM AND TEST RESULTS

Four conventional IL oedometer tests were carried out using four laboratory prepared Kaolin samples. These samples were prepared by using a consolidometer of 20 cm in diameter and 6 cm in height. These samples were preloaded to 132 kPa in the consolidometer before unloaded in steps to zero loads with sufficient time allowed for rebounds, and then extruded out of the ring and cut into four one-quarter pieces. The initial void ratios, water contents, and degree of saturations of the samples are very similar and are listed in Table 1. Each sample was carefully trimmed with a wire-saw to prepare a specimen into the oedometer ring. Two samples for the Test C-1 and the Test C-2 were not disturbed. The sample for the Test C-3 was heavily disturbed (*i.e.*, dropped to table several times and pressed downward and sideway several times) before trimming into a specimen ring. The sample for the Test C-4 was very slightly disturbed (*i.e.*, hit by a ceramic pedestal a few times) before trimming. Values of load increment ratio (LIR) of 3 and 0.125 were used in Test C-2, whereas LIR of 1 is used in Test C-1 and LIR of 0.677, 1, and 1.677 were used in Test C-3. In test C-4, LIR of 1 was used and two cycles of unload-reload were executed during the test. Liquid limit and plastic limit were determined from portions of the Kaolin samples as 76% and 34%, respectively. Figure 2 is a scanning electron microphotograph of the Kaolin sample showing platy shape particles and large voids in between particles. The specific gravity of the Kaolin sample was determined as 2.63.

2.1 ε_v-log *t* Curves

The measured data of LVDT and time can readily be converted to obtain ε_v-log t curves for each IL oedometer test. The initial height of the specimen is used in computing the value of strain for all loading increments. Four sets of ε_v-log t curves are shown in Figs. 3 ~ 6 for Tests C-1 ~ C-4, respectively. Each of these curves shows an inflection point so that the time of end of primary consolidation is determined using graphical construction method and the results are listed in Tables 2 ~ 5. It is clear from Tables 2 ~ 5 that the durations of primary consolidation of many loading incrrements are around 10 ~ 20 minutes. The first data point

Table 1 Volume and weight relationships of the oedometer specimens

Test no.	e_0	w_0 (%)	S_r (%)
C-1	1.534	58.1	99.6
C-2	1.527	57.4	99.4
C-3	1.517	57.0	99.7
C-4	1.530	57.5	99.6

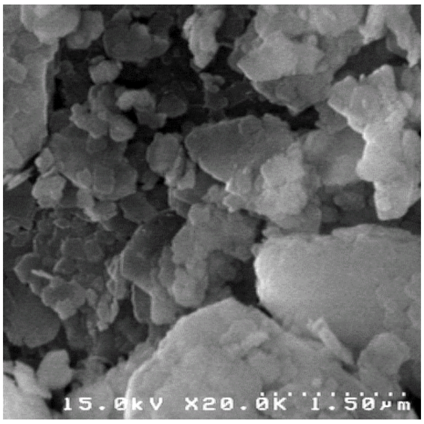

Fig. 2 Scanning electron microphograph of the Kaolin sample

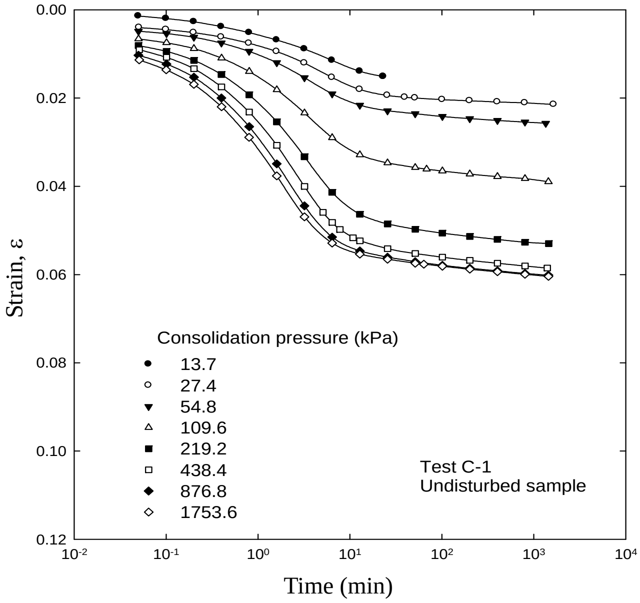

Fig. 3 Measured time rate of strain relationships for Test C-1

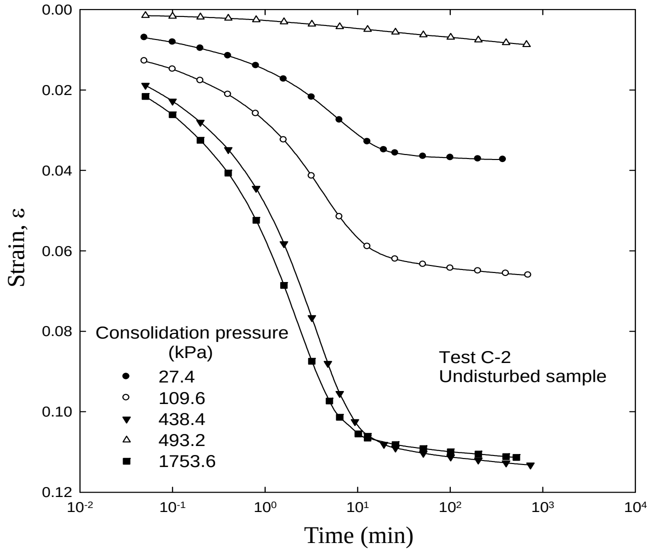

Fig. 4 Measured time rate of strain relationships for Test C-2

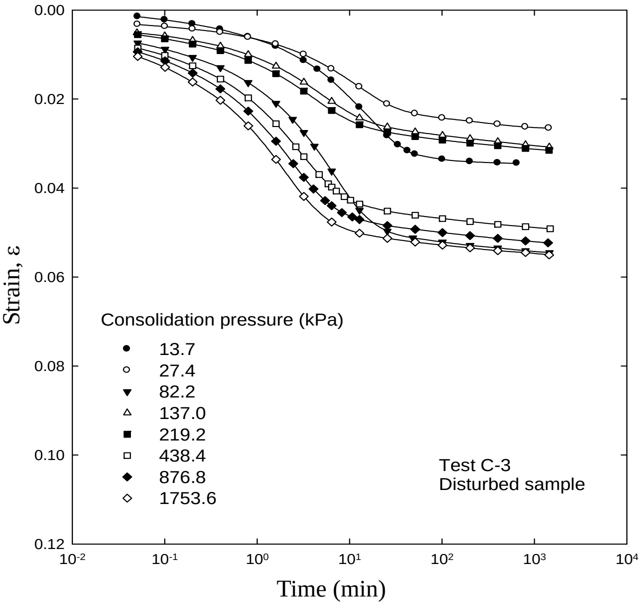

Fig. 5 Measured time rate of strain relationships for Test C-3

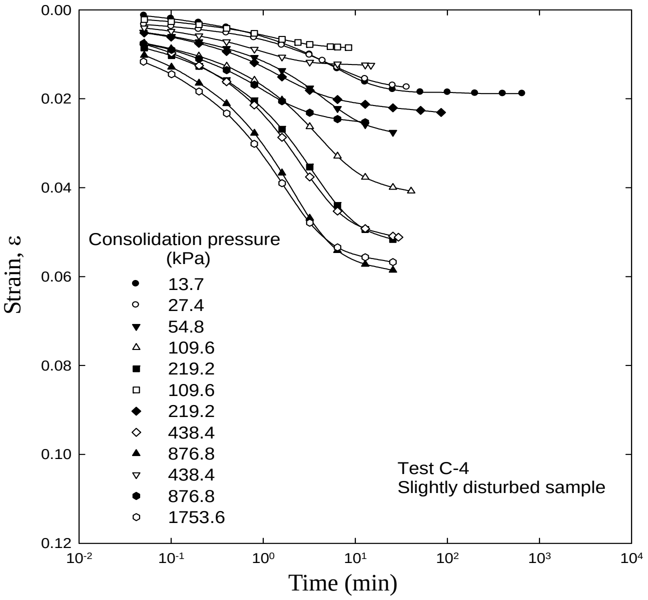

Fig. 6 Measured time rate of strain relationships for Test C-4

Table 2 Measured strain rates of Test C-1 (undisturbed sample)

Consolidation pressure (kPa)	LIR	$\dot{\varepsilon}_{0.025}$ (1/min)	$\dot{\varepsilon}_{eop}$ (1/min)	$\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$	t_{eop} (min)
27.4	1	0.0175	0.000050	350	26.8
54.8	1	0.0157	0.000095	165	20.0
109.6	1	0.0262	0.000119	220	20.0
219.2	1	0.0471	0.000130	362	21.5
438.4	1	0.0647	0.000200	324	15.5
876.8	1	0.0733	0.000200	367	13.0
1753.6	1	0.0832	0.000208	400	11.7

Table 3 Measured strain rates of Test C-2 (undisturbed sample)

Consolidation pressure (kPa)	LIR	$\dot{\varepsilon}_{0.025}$ (1/min)	$\dot{\varepsilon}_{eop}$ (1/min)	$\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$	t_{eop} (min)
27.4	–	0.0304	0.000060	507	33.0
109.6	3	0.0565	0.000130	435	24.6
438.4	3	0.1170	0.000200	585	19.3
493.2	0.125	0.0042	0.000230	18	3.6
1753.6	2.556	0.1057	0.000300	352	12.5

Table 4 Measured strain rates of Test C-3 (disturbed sample)

Consolidation pressure (kPa)	LIR	$\dot{\varepsilon}_{0.025}$ (1/min)	$\dot{\varepsilon}_{eop}$ (1/min)	$\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$	t_{eop} (min)
27.4	1	0.0123	0.000036	342	54.0
82.2	1.677	0.0565	0.000078	724	31.0
137.0	0.677	0.0147	0.000100	147	24.6
219.2	1	0.0318	0.000120	265	18.9
438.4	1	0.0390	0.000160	244	16.4
876.8	1	0.0472	0.000210	225	13.2
1753.6	1	0.0893	0.000280	319	11.2

Table 5 Measured strain rates of Test C-4 (slightly disturbed sample)

Consolidation pressure (kPa)	LIR	$\dot{\varepsilon}_{0.025}$ (1/min)	$\dot{\varepsilon}_{eop}$ (1/min)	$\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$	t_{eop} (min)
27.4	1	–	–	–	–
54.8	1	–	–	–	–
109.6 (Comp.)	1	0.0267	0.000230	116	16.0
219.2 (Comp.)	1	0.0390	0.000170	229	20.0
54.8	–	–	–	–	–
109.6 (Recomp.)	1	0.0144	0.000430	33	3.1
219.2 (Recomp.)	1	0.0216	0.000230	94	8.0
438.4 (Comp.)	1	0.0400	0.000220	182	13.6
876.8 (Comp.)	1	0.0616	0.000160	385	12.0
219.2	–	–	–	–	–
438.4 (Recomp.)	1	0.0318	0.000420	76	3.0
876.8 (Recomp.)	1	0.0325	0.000400	81	5.0
1753.6	1	–	–	–	–

shown in each of the ε_v-log t curves corresponds to a rather short time of consolidation of 0.05 minute. This was done with a data acquisition system. The strain at 0.05 minute is divided by 0.05 minute to compute for the value of initial strain rate $\dot{\varepsilon}_{0.025}$, which corresponds to an average strain rate between 0 and 0.05 minute of primary consolidation. It may be noted that the strain values for all increments at this early time increases with increasing the consolidation pressure. Due to the high value of LIR of 3 used, the final strain of the loading increment in Test C-2 is much higher than the loading increment in Test C-1 and Test C-3 with the same consolidation pressure.

2.2 End-of-Primary $e - \log \sigma'_v$ Relationships

In order to obtain the value of compression index C_c for defining the compressibility ratio C_α / C_c, the end-of-primary void ratio for each loading increment is evaluated from its ε_v-log t curve and then plotted against the consolidation pressure. The end-of-primary e - $\log \sigma'_v$ relationships for Tests C-1 ~ C-4 are shown in Fig. 7. The effect of sample disturbance is clearly shown in Fig. 7 that the compression curve of Test C-3 is on the left hand side of the compression curves of Tests C-1 ~ C-2. The compression curves of Test C-1, Test C-2, and Text C-4 are very close to each other, which mean that the values of LIR and consolidation time have little or no effect on the end-of-primary e - $\log \sigma'_v$ relationship, and the degree of sample disturbance in Test C-4 is insignificant. For Test C-1, the specimen was loaded from 109.6 to 438.4 kPa with two increments, and the total consolidation time to the end of primary under 438.4 kPa was 1450 minutes. Whereas for Test C-2, the specimen was loaded from 109.6 to 438.4 kPa with only one increment, and the consolidation time to the end of primary consolidation is merely 10 minutes. The tremendous difference in the time of consolidation does not seem to affect the end-of-primary void ratio.

2.3 $c_v - \log \sigma'_v$ Relationships

The value of coefficient of consolidation is evaluated in this study by applying the Casagrande's curve fitting method on the ε_v-log t curve. The obtained results for Tests C-1 ~ C-3 are shown in Fig. 8. It can be seen from Fig. 8 that sample disturbance greatly reduces the value of coefficient of consolidation during first few loading increments and does not seem to affect it during latter increments. This is consistent with the past experience that the effect of sample disturbance diminishes with increasing the consolidation pressure.

2.4 C_α / C_c Ratio

The C_c values are evaluated from the end-of-primary e - $\log \sigma'_v$ relationships on the data points shown in Fig. 7. The maximum value of C_c determined is 0.468, about one-third of the value of initial void ratio. The value of secondary compression index C_α for each loading increment is determined from its $C_{\alpha\varepsilon}$ value multiplied by $(1 + e_0)$, where e_0 is the initial void ratio of the specimen. To determine a representative value of C_α / C_c for the soil tested, data of C_α and C_c obtained from each loading increment are plotted against each other, as shown in Fig. 9. The determined value of C_α / C_c is 0.016, a rather low value for high plasticity clay.

3. STRAIN RATE BEHAVIORS

The ε_v-log t curves shown in Figs. 3 ~ 6 can be used to compute for strain rates in the early stage of primary consolidation and at the end of primary consolidation. Tables 2 ~ 5 also summarize the computed initial strain rate $\dot{\varepsilon}_{0.025}$ at time of 0.025 minute of consolidation and the strain rate $\dot{\varepsilon}_{eop}$ at the end-of-primary consolidation. Large values of $\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$ in Tables 2 ~ 5 indicate an acute change of strain rates from the beginning till the end of primary consolidation. In Tables 2 ~ 3, the $\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$ values

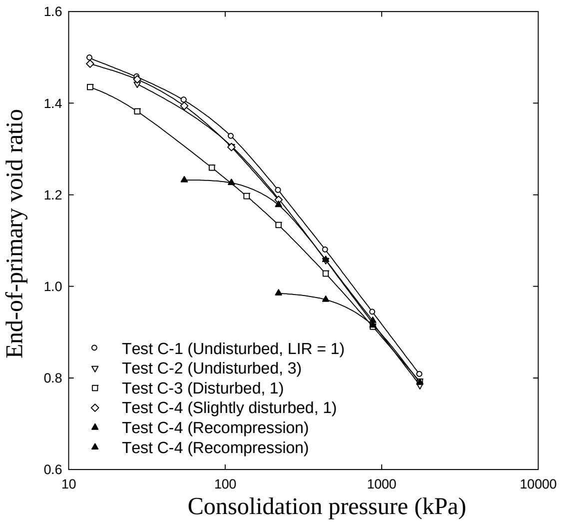

Fig. 7 **Determined end-of-primary compression curves with compression and recompression**

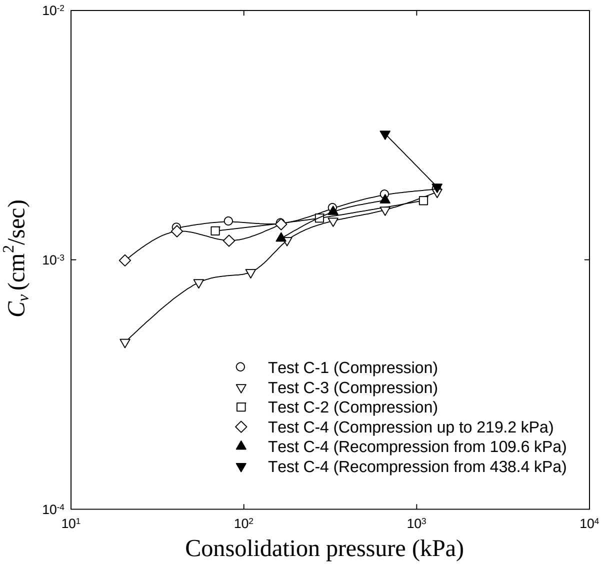

Fig. 8 **Determined coefficient of consolidation from Tests C-1-C-4**

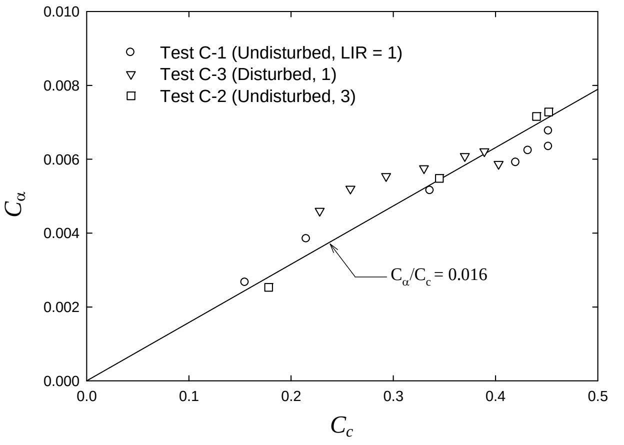

Fig. 9 **Determined relationship between C_α and C_c for the Kaolin samples**

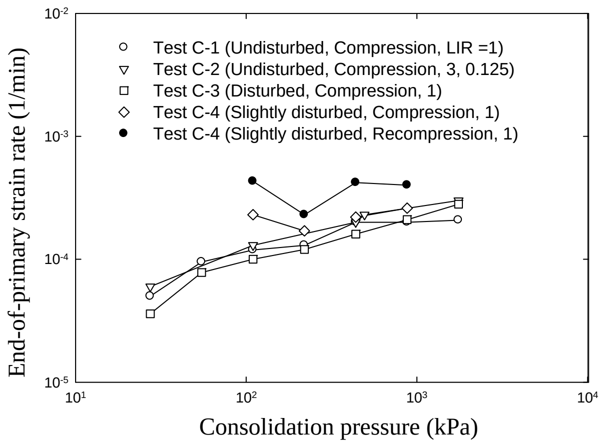

Fig. 10 **Determined relationships between end-of-primary strain rate and consolidation pressure**

range from 165 to 585, with most values greater than 300; the small $\dot{\varepsilon}_{0.025}/\dot{\varepsilon}_{eop}$ value of 18 in Table 3 corresponds to a small LIR of 0.125. The $\dot{\varepsilon}_{0.025}/\dot{\varepsilon}_{eop}$ values in Table 4 from the disturbed sample are in general smaller than those in Tables 2 and 3 from the undisturbed sample. Except that a large ratio of 724 in Table 4 for the disturbed sample is apparently the result of a high $\dot{\varepsilon}_{0.025}$ value due to high LIR of 1.677 and a low $\dot{\varepsilon}_{eop}$ value in recompression range. In Table 5, it can be seen that the $\dot{\varepsilon}_{0.025}/\dot{\varepsilon}_{eop}$ values in recompression are much smaller than those in compression. This is because, in general, the values of $\dot{\varepsilon}_{0.025}$ are higher in compression due to relative large potential of void ratio change during primary consolidation, and the values of $\dot{\varepsilon}_{eop}$ are lower in compression due to longer time to the end of primary consolidation t_p.

An implication of these $\dot{\varepsilon}_{0.025}$ strain rate values is that CRS oedometer tests should not be carried out with strain rates near them. Otherwise tremendous excess pore water pressure is expected and renders severe problems in data reduction. Note that in the early stage of primary consolidation the difference in excess pore water pressures between two ends of the specimen is around its maximum, and the distribution of excess pore water pressures between two ends of the specimen is highly nonlinear. When $\dot{\varepsilon}_{eop}$ is used to carry out the CRS oedometer test, it is expected that little or zero excess pore water pressure will be generated and the end-of-primary $e - \log\sigma'_v$ relationship will be obtained. However, in order to evaluate the coefficient of consolidation as a function a consolidation pressure (*e.g.*, Smith and Wahls 1969; Gorman *et al*. 1978; Armour and Drnevich 1986), the CRS oedometer is generally carried out using a strain rate somewhat higher than $\dot{\varepsilon}_{eop}$ so that some amounts of excess pore water pressures are generated at the bottom of the specimen and the reduced data of averaged effective consolidation stress remains representative of the entire specimen. In this regard, Mesri and Feng (1992) have analyzed the results of a number of CRS oedometer tests, and accordingly recommended using a strain rate of $10\,\dot{\varepsilon}_{eop}$ for the CRS oedometer test. On the other hand, the values of C_v, C_α, and C_c may be used to estimate the end-of-primary strain rate.

The $\dot{\varepsilon}_{eop}$ data listed in Tables 2 ~ 5 are plotted in Fig. 10 against their corresponding consolidation pressures, for the purposes of observing the behavior of $\dot{\varepsilon}_{eop}$ as a function of consolidation pressure, stress history, sample disturbance, and load increment ratio. Note that the samples used in this study were prepared in the laboratory to have a preconsolidation pressure of 132 kPa. It is observed from Fig. 10 that, for consolidation pressures greater than 132 kPa, the end-of-primary strain rates $\dot{\varepsilon}_{eop}$ in general increases slightly with increasing the consolidation pressure. This is in general consistent with the observed results of smaller t_p for higher consolidation pressures, as can be seen in Tables 2 ~ 5. For consolidation pressures smaller than 132 kPa, the specimens are in overconsolidated state and an increase in $\dot{\varepsilon}_{eop}$ with increasing the consolidation pressure, with a slightly higher rate of increase, is observed. However, there are four measurements made in Test C-4 that the specimen is also in overconsolidated sate (recompression), and the results show slightly higher values of $\dot{\varepsilon}_{eop}$ as compared to those in normally-consolidated state (compression), as shown in Fig. 10. This is because that this recompression is executed during the oedometer test after a small amount of rebound due to unloading; the rebound during sample preparation is executed in the 20-cm diameter consolidometer with all loads removed, so that a higher compressibility (*i.e.*, smaller $\dot{\varepsilon}_{eop}$) is observed during recompression in the oedometer test for pressures smaller than the preconsolidation pressure. It is seen from Fig. 10 that sample disturbance slightly reduces the value of $\dot{\varepsilon}_{eop}$ as the data of Test C-3 are in general slightly smaller than those of other Tests. The slight disturbance made to the sample of Test C-4 was probably insignificant since $\dot{\varepsilon}_{eop}$ values of Test C-4 are about the same as those of Test C-1 and Test C-2. These data also indicate a no-effect of load increment ratio on $\dot{\varepsilon}_{eop}$. For good quality undisturbed sample taken with thin-wall tubes or by block sampling, the sample disturbance is limited and its effect on end-of-primary strain rate would probably be limited. Finally, it is evaluated from the results in Fig. 10 that there is an increase in $\dot{\varepsilon}_{eop}$ from the preconsolidation pressure (*i.e.*, 132 kPa) to the maximum consolidation pressure (*i.e.*, 1753.6 kPa) by approximately only 2 ~ 3 times. Thus, in view of the observed $\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$ values of hundreds reported and discussed in previous paragraphs, it is evident that running the CRS oedometer test with a constant strain rate slightly higher than $\dot{\varepsilon}_{eop}$ is not far away from the incremental loading end-of-primary condition.

The composition of natural clays is expected to be different from the composition of the Kaolin samples tested. In the absence of oedometric strain rate data on natural clays, it is not known at this point whether the results of observations made on the Kaolin samples could be quantitatively applied to natural clays. Further tests on natural clays and organic soils are needed to study the effect of soil composition on oedometric strain rate behavior. From a qualitative point of view, it may be noted that the theoretical relationship between one-dimensional time-rate of consolidation and permeability and compressibility holds true for saturated clays in general. Thus, it is likely that the $\dot{\varepsilon}_{0.025} / \dot{\varepsilon}_{eop}$ strain rate ratio and the $\dot{\varepsilon}_{eop}$ strain rate behaviors are not strongly dependent of the soil composition.

4. CONCLUSIONS

The following conclusions are based on the test results and discussions presented in previous paragraphs for the Kaolin samples：

1. The oedometric consolidation strain rate at 0.025 minute is within 116 to 724 times of the end-of-primary strain rate, with load increment ratios greater than 0.677; a low strain rate ratio of 18 is observed for a small load increment ratio of 0.125. For cases of recompression induced during oedometer tests, the strain rate at 0.025 minute is within 33 to 94 times of the end-of-primary strain rate, with load increment ratios all equal to 1. These strain rate ratios provide information on the fastest strain rate limits for running the CRS oedometer test to study the effect of strain rate on clay compressibility.
2. Load increment ratio has little or no effect on the end-of-primary strain rate. Sample disturbance tends to reduce the end-of-primary strain rate for the first few increments under low consolidation pressures; this effect is reduced during latter increments at higher consolidation pressure. Stress history affects end-of-primary strain rate in two different conditions: Overconsolidation induced during sample preparation tends to reduce the end-of-primary strain rate, and overconsolidation induced by unloading during oedomter test tends to increase the end-of-primary strain rate.
3. The end-of-primary strain rate increases by only about 2 ~ 3 times with increasing the consolidation pressure from the preconsolidation pressure of 132 kPa to the maximum consolidation pressure of 1753.6 kPa. Thus, running the CRS oedometer test with a strain rate slightly higher than $\dot{\varepsilon}_{eop}$ is expected to obtain test results comparable to that obtained from the incremental loading consolidation test.

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