THE DEVELOPMENT OF SHEAR STRENGTH FOR SEDIMENTARY SOFT CLAY WITH RESPECT TO AGING EFFECT

YI XIN TANG\(^{1}\) and TAKASHI TSUCHIDA\(^{1}\)

ABSTRACT

It is widely known that shear strength of clay continues to increase after the end of primary consolidation. Some reports show that the strength gain is remarkable especially for marine clays near surface of natural deposits. However, not much is understood on this subject.

An attempt has been made to reveal the phenomenon of strength gain with time. The developing mechanism of shear strength is characterized by assuming that shear strength gain during the secondary process can be understood as two contributing components: secondary compression and effect of cementation.

The increase rate of shear strength for a sedimentary from clay slurry is investigated. It is found that a remarkable increase in shear strength is obtained during the secondary process, though little change takes place in water content. Based on experimental data, the authors suggest that cementation effect on shear strength gain is in relation with overburdened pressure \(p_0\). The increasing rate can be expressed simply by \(\Delta c_u/\Delta \log t = 0.3 \cdot \sqrt{p_0}\). This relation is verified as nearly valid when overburdened pressure is extended to \(p_0=0.01 - 1000\) kPa.

Key words: aging, cementation effect, clays, secondary compression (IGC: D6)

INTRODUCTION

In harbour areas, engineers often meet problems such as siltation, sedimentation etc., which may cause traffic obstacles along the waterways. The most practical measure is to dredge these deposits away. Recently, more and more concerns have become concentrated on coastal contamination. One measure taken is to overlay the contaminated deposits with clean sand, so as to improve the coastal environment. In such cases, it is necessary to predict the shear strength and compression characteristics of the very soft layer near the surface of marine ground.

Gomyo et al. (1990) investigated shear strength on undisturbed samples with depths of \(z=0-60\) cm. Figures 1(a), (b) are typical results for clay samples taken from the Tokyo Bay seabed, with shear strengths increasing from 0.5 kPa near the surface to 1.5-2 kPa around a depth of 50 cm. They also carried out a sedimentation experiment on Tokyo Bay clay arranged with an initial water content of 1000%. Figure 1(c) gives the shear strength measured when primary consolidation under self weight is completed. The shear strength measured in the laboratory turns to be 0.015-0.1 kPa, merely 1 tenth of that in situ as shown in Fig. 1(a), (b). This is a surprising discrepancy in shear strength. Gomyo et al. consider that the extremely large shear strength in situ is due to flocculation during sedimentation, or organic substances which act as an agent enhancing coagulation.

Attempts have been made to obtain larger shear strength or consolidation yield pressure by utilizing the technique of high temperature consolidation. Tsuchida et al. (1989) performed consolidation tests on a clay sample, which was obtained under high temperature consolidation. Figure 2 shows the compression curves obtained for a sample previously consolidated at high temperature and one consolidated at room temperature, compared with that on an undisturbed sample. We can see that the sample that experienced high temperature consolidation exhibits aspects of high degree structure, such as larger void ratio, distinctive yielding and larger compressibility after the yielding, which resemble the undisturbed sample.

However, it should be noted that such efforts partially succeeded in reproducing the mechanical characteristic of natural deposits, because many factors affected the structure formation during the depositional process. One of the important factors is the rate of deposition, which may range within 0.01-20 cm/year (e.g. 1.6-11.4 cm/year in Tokyo Bay, Kimura et al. 1987). If the rate of deposition is very small, the structure originated from the flocculation remains almost intact, and the bonding becomes stronger through the secondary process. Conversely, if the rate of deposition is relatively large, the
overburdened pressure increases so rapidly that the bonding due to cementation may not be developed well. Clay deposits would not be able to form a high degree structure in the latter situation.

In the present study, an examination is made on a series of available shear strength data measured on sediments with various degrees of secondary consolidation. This results in the fact that the rate of increase in shear strength depends on overburdened pressure. The larger the overburdened pressure, the greater the increase rate of shear strength. At the same time, the water content decreases slightly during the secondary period although a substantial increase in shear strength is obtained.

These results suggest that shear strength gain as a consequence of aging effect consists of two components: one is attributed to volumetric compression, while the other is attributed to cementation, namely chemical bond. The increasing rate of shear strength for the later contribution could be expressed approximately by \( \frac{\Delta c_u}{\Delta \log t} = 0.3 \sqrt{p_0} \). This relation is discussed on the basis of available data concerning a large range of pressure, e.g. \( p_0 = 0.01 - 1000 \) kPa.

**DISTINCT CONTRIBUTIONS TO STRENGTH GAIN ASSOCIATED WITH AGING**

*Volumetric Compression Versus Cementation during Secondary Process*

When excess pore water pressures have almost dissipated, clay layers will continue to settle. This phenomenon is called secondary compression. Since it is accompanied by a reduction in void ratio, and simultaneously in water content, some increase in shear strength is expected to gain during the secondary process, without increase in effective pressure. Figure 3 illustrates an instant compression curve, which is imaged for young clay. If the pressure is increased until \( p_v \), and ceased at point A for a long time, the void ratio will reduce along the path AB, accompanied with secondary compression \( \Delta e_v \). Mesri (1979), Yasuhara and Ue (1983) proposed methods to evaluate the portion of strength gain originating from this volumetric compression.

At the same time, however, formation change and chemical alteration take place among soil particles under conditions not related with volumetric compression. These changes have the effect of toughening particle linkages, namely bonding and will certainly make a contribution to strength gain. The component of strength gain not associated with volumetric compression is classified as cementation, in a very broad sense in the present study. In this sense, the cementation stated here includes various factors, such as flocculation, thixotropy, leaching and so on. All kinds of actions are influenced by composition of clay, geological circumstance, or temperature environment. The authors intend to reveal how cementa-
tion promotes shear strength during the secondary process in a macroscopic sense, rather than by each factor. Figure 3 presents a typical compression curve for an undisturbed sample. When subjected to additional pressure increases, the clay in situ generally shows compression characteristic as shown by curve BCDE. Normally consolidated aged clays usually do not yield at C on the instant compression curve by a pressure $p_0$, but at D with a larger pressure $p_c$. Here, the authors define the difference $(p_c-p_0)$ as the result of secondary compression $\Delta e_c$, and $(p_c-p_l)$ as the result of cementation. The summary $(p_c-p_0)$ is the whole effect of aging obtained during the secondary process.

**Evaluation of Shear Strength Gain Due to Secondary Compression**

Yasuhara and Ue (1983) postulated that the quasi-consolidation induced by secondary compression be equivalent to overconsolidation due to stress release, and derived a method to evaluate shear strength gain due to secondary compression:

$$\frac{c_u}{p_0} = \beta \left( \frac{c_u}{p_0} \right)_{NC} \left( \frac{t}{t_p} \right)^{\frac{c_u}{p_0} - A}$$  \hspace{1cm} (1)

in which, $C_s$, $C_c$ and $C_u$ are compression index, swelling index and coefficient of secondary compression, respectively; $(c_u/p_0)_{NC}$ denotes ratio of shear strength increase for normally consolidated young clay. The gradient of $(c_u/p_0)_{NC}$ for the linear relation in Fig. 4(a) corresponds to the instant compression curve in Fig. 3, and $t_p$ should be referred to the ending time of primary consolidation.

As shown in Fig. 4(b), an experimental constant $A$ is used to describe the decline of shear strength due to stress release. For most clays, a value of $0.7 \sim 0.9$ is deemed to be suitable for constant $A$. Hanzawa and Kishida (1981) suggested that constant $A$ be equal to 1.0 if $OCR$ is deduced through the secondary process:

$$\left( \frac{c_u}{p_0} \right)_{NC} = OCR^A$$  \hspace{1cm} (2)

**Shear Strength Gain Associated with Cementation**

Another constant involved in Eq. (1) is coefficient $\beta$, which is important in the present study. Yasuhara et al. used it to indicate the degree of cementation. It is apparent that coefficient $\beta$ expresses the magnitude of $(p_c-p_l)$, which is sometimes named a leap departing from the instant compression curve CD as shown in Fig. 3. Muragami (1979) conducted a particular one-dimensional consolidation on Nagasaki loam, with the result that the value of $\beta$ was found to vary between 1.0 and 1.1. In fact, a value of $\beta=1.0$ was adopted in the paper by Yasuhara and Ue (1983). Obviously, assuming $\beta=1.0$ means that the effect of cementation is not taken into account.

Speaking practically, consolidation pressures applied on reconstituted samples are somewhat greater than 50 kPa in triaxial experiments, usually between 100 kPa and 1000 kPa. Substantial secondary compression and, subsequently, an appreciable increase in shear strength are obtainable when long term consolidations are perpetuated under such pressures. Possibly shear strength gain deduced by cementation disappears behind that due to
secondary compression. This is the difficulty in detecting the tendency of cementation effect.

Mesri (1995) proposed the following relation to examine the contribution of thixotropic hardening, in addition to secondary compression:

$$\frac{p_c}{p_0} = \left(1 - \left(\frac{t}{t_p}\right)^k\right)^{c_t}$$  \hspace{1cm} (3)

By comparing Eq. (1) and Eq. (3), it can be found that coefficient $\beta$ in Eq. (1) is replaced by the term of $(t/t_p)^k$ in Eq. (3). Mesri suggested a value of $\beta=0.02$ is proper to prediction of thixotropic hardening through secondary process.

In the present study, the effect of cementation is examined on the basis of shear strength data measured on sedimentary deposits, as well as data measured from clay samples consolidated under small pressures. Shear strength gain due to cementation is estimated by subtracting the effect of volumetric compression from shear strength increase actually observed during the secondary process.

**SEDIMENTATION EXPERIMENT ON A DREDGED SOIL**

To evaluate the characteristics of consolidation and shear strength for dredged spoils, a series of sedimentation and consolidation experiments were conducted on Kumamoto clay by the 4th District Port Construction Bureau, Ministry of Transport. The authors make use of the information given in the report.

Liquid, plastic limits and plastic index of Kumamoto clay after rearrangement were $w_L=95\%$, $w_p=38\%$ and $I_p=57$, respectively. This material was remolded as slurries with initial water content of 700\%, 1000\% and 1500\%. The slurries were then poured into acrylic cylinders of 33 cm in diameter and 200 cm in height. As the experiment started, the height of interface between the upper water and the sedimentary material was observed. Settlement curves are presented in Fig. 5. It is clear that the whole process divides into three periods; 1) sedimentation, 2) primary consolidation, and 3) secondary consolidation. For the cases of a given initial water content, 4 sedimentary columns were prepared respectively, and consolidated for different durations of consolidation.

After the sedimentation and then consolidation under self-weight, vane shear strength and water content were measured. Vane shear tests were conducted at: $t_0$, 10 days, completion of sedimentation; $t_1$, by the end of primary consolidation (EOP); $t_2$, 30 days after EOP; and $t_3$, 90 days after EOP. The elapsed time at which shear strength and water content were measured is listed in Table 1. The measuring pitch along depth was 10 cm in vane shear tests (width 2 cm, height 4 cm, rotating rate 6 deg./min). When the vane shear test was finished, the sediment was sliced layer by layer in 5 cm pitch, and 3 representative samples were taken from each slice for water content measurement.

Figure 6 displays shear stress against rotating angle of vane plate for the sediments from slurry of $w_0=1000\%$. It can be seen that shear strength increases substantially with elapsed time. In more detail, the shearing behavior for the sample at $t_0$, as shown in Fig. 6(a), is very similar to that when a clay is tested immediately after remolding. That is, the shearing curve does not exhibit apparent peak resistance against rotating deformation, while the other results in this figure present larger shear strength and more apparent peak resistance.

Figure 7 shows shear strength $c_t$ plotted with overburdened pressure $p_o$, which was estimated by use of submarine unit weight $\gamma'$ with the following relation:

$$p_o = \sum \gamma' A_z$$  \hspace{1cm} (4)

Where submarine unit weight $\gamma'$ is calculated on the basis of water content $w$ by the following formula:

$$\gamma' = \frac{G_s - 1}{1 + G_s w/100} \gamma_w$$  \hspace{1cm} (5)

Here, $G_s$ is specific gravity of clay particle, and $\gamma_w$ is unit weight of pore water.

**Table 1. Elapsed time, settlement and estimated consolidation degree when shear strength measurement was conducted**

<table>
<thead>
<tr>
<th>$w_0$ (%)</th>
<th>Terms:</th>
<th>$t_0$</th>
<th>$t_1$</th>
<th>$t_2$</th>
<th>$t_3$</th>
<th>Final</th>
</tr>
</thead>
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<tr>
<td>700</td>
<td>Elapsed time (day)</td>
<td>10</td>
<td>53</td>
<td>83</td>
<td>125</td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Settlement (cm)</td>
<td>111.2</td>
<td>126.3</td>
<td>127.6</td>
<td>128.6</td>
<td>130.2</td>
</tr>
<tr>
<td></td>
<td>Deg. of cons. (%)</td>
<td>85.4</td>
<td>97.0</td>
<td>98.0</td>
<td>98.8</td>
<td>100</td>
</tr>
<tr>
<td>1000</td>
<td>Elapsed time (day)</td>
<td>10</td>
<td>35</td>
<td>65</td>
<td>125</td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Settlement (cm)</td>
<td>137.3</td>
<td>144.4</td>
<td>145.8</td>
<td>147.1</td>
<td>148.4</td>
</tr>
<tr>
<td></td>
<td>Deg. of cons. (%)</td>
<td>92.5</td>
<td>97.3</td>
<td>98.2</td>
<td>99.1</td>
<td>100</td>
</tr>
<tr>
<td>1500</td>
<td>Elapsed time (day)</td>
<td>10</td>
<td>26</td>
<td>56</td>
<td>116</td>
<td>$\infty$</td>
</tr>
<tr>
<td></td>
<td>Settlement (cm)</td>
<td>151.2</td>
<td>157.1</td>
<td>160.5</td>
<td>162.0</td>
<td>163.4</td>
</tr>
<tr>
<td></td>
<td>Deg. of cons. (%)</td>
<td>92.5</td>
<td>96.1</td>
<td>98.2</td>
<td>99.1</td>
<td>100</td>
</tr>
</tbody>
</table>
It may be doubtful whether or not the overburdened pressure $p_0$ estimated by Eq. (4) is identical with the actual effective stress acting. The authors evaluated the degree of consolidation on the basis of observed settlement. The result is presented in Table 1. The degree of consolidation reaches 85–92% by the moment of $t_0$, and
96–99% when consolidation progresses beyond EOP, e.g. \( t_1, t_2, t_3 \). That is to say, Eq. (4) will, on average, overestimate \( p_0 \) value by 15–8% by the moment \( t_0 \) and 4–1% after EOP. The error in the latter situations is negligible.

A tendency is found from Fig. 7 that shear strength \( c_u \) increases with overburdened pressure \( p_0 \) and with consolidation duration \( t \), as well. The relation between shear strength and overburdened pressure is assumed to be linear in Fig. 7.

Figure 8 shows the distribution of water content along depth. Water content decreases with depth mainly because of the increment of overburdened pressure in deeper layers. An important phenomenon to be mentioned here is that the reduction in water content is insignificant after EOP. Regarding the behaviors of shear strength and water content shown in Figs. 7 and 8, it can be said that the increase of shear strength after EOP should be explained as less due to the void ratio reduction by secondary compression, than to the effect of cementation.

Figure 9 shows the shear strength data in Fig. 7 re-plotted against elapsed time for given constant overburdened pressure \( p_0 \). This result is evidence that shear strength increases steadily with elapsed time in log scale. More interestingly, the increasing rate \( \Delta c_u / \Delta \log t \) depends on the magnitude of overburdened pressure \( p_0 \). The greater the overburdened pressure, the greater the increasing rate \( \Delta c_u / \Delta \log t \). The values of \( \Delta c_u / \Delta \log t \) for \( p_0 = 0.1, 0.2, \ldots, 1.0 \) kPa are determined, and shown in Fig. 10. The data in Fig. 10 is re-plotted in a double log style as shown in Fig. 11. A correlation between \( \Delta c_u / \Delta \log t \) and \( p_0 \) can be expressed approximately by a simple relation (both \( c_u \) and \( p_0 \) are in kPa).

\[
\frac{\Delta c_u}{\Delta \log t} = 0.3 \sqrt{p_0}
\]  

Equation (6) describes how shear strength is developed during the secondary process in a very simple form. This relation is derived on the basis of shear strength meas-

![Fig. 8. Water content remaining nearly unchanged after EOP](image)

![Fig. 9. Shear strength increasing with elapsed time](image)

![Fig. 10. Increasing rate of shear strength, \( \Delta c_u / \Delta \log t \), depending on overburdened pressure \( p_0 \)](image)
STRENGTH GAIN WITH AGING

Fig. 11. Experiment relation between \( \Delta c_u/\Delta \log t \) and \( p_0 \)

\[
(\Delta c_u/\Delta \log t) = 0.3 \sqrt{p_0}
\]

Overburdened pressure \( p_0 \) (kPa)

Fig. 12. Consolidation settlements under small overburdened pressures

SHEAR STRENGTH GAIN UNDER SMALL PRESSURES

In usual sedimentation experiments, overburdened pressure is limited below 1 kPa. To investigate the characteristics of shear strength gain under pressures a little larger, experiments need to be performed in other styles. For this purpose, consolidations were conducted under small pressures, and development of shear strength was investigated on soft clay samples, which had experienced various periods of secondary process. By small pressure here, we mean \( p_0 = 1-10 \) kPa.

Conventional Oedometer Consolidation

The material used in oedometer consolidations of small pressure was Honmoku clay taken from Yokohama Bay. The clay was reconstituted by removing coarse particles. Liquid limit \( w_l \) was measured at about 100%. Clay slurry was prepared with an initial water content of \( w_0 = 200\% \). Soft clay samples were obtained in such a manner that slurry was pre-consolidated primarily under a pressure of 2 kPa within oedometers, and then trimmed to an initial height of 2 cm.

Samples thus obtained were subjected to pressures of 2, 5, 10 kPa, and consolidated respectively. Figure 12 presents settlement curves for the soil clay samples consolidated under small pressures. Suppose the inflection of settlement curve corresponds to the point of EOP, it can be read that the time required for EOP is \( t_e = 200, 96, 68 \) minutes, for \( p_0 = 2, 5, 10 \) kPa, respectively; the larger the pressure applied is, the faster the consolidation progresses.

For each case, one-dimensional consolidation was kept for different degrees of secondary consolidations. Consolidation duration was set to be 4, 12 hours and 1, 2, 4, 10 days. When consolidation was terminated, shear strength and water content were measured. Considering clay samples obtained were still fairly weak and sample size was limited, it was impossible to measure shear strength by means of conventional triaxial or vane shear tests. Instead, a fall cone technique, which has found practical application in measuring liquid limit of clays, was introduced to evaluate shear strength. A cone device was installed with the apex just touching the sample surface. Then it was dropped and the penetration into the sample was monitored. Shear strength can be determined with the relation proposed by Hansbo:

\[
c_u = k \frac{W}{d^2}
\]

where \( W \) is weight of fall cone unit (0.97 N), \( d \) is the penetration after falling for 5 seconds, and \( k \) is a coefficient which depends on the angle of cone apex. The cone presently used is of 60 degrees at the apex, and \( k \) is assigned at 0.3. As can be observed from Fig. 12, the thickness of samples varied with consolidation pressure and consolidation duration, ranging within 1.65–1.8 cm. The samples obtained were not large enough as compared with those used in the liquid limit test. When the cone device was dropped, the clearance beneath the cone apex remained larger than 1.0 cm in most cases. The authors believe that the influence of sample limitation is insignificant to the study of shear strength gain with aging.

Figure 13 presents shear strength measured by the fall cone method. It is clear that shear strength increases with elapsed time. Moreover, there is a tendency that increasing rate of shear strength \( (\Delta c_u/\Delta \log t) \) changes with applied pressure \( p_0 \); the larger the pressure is, the greater the increasing rate becomes. It should be remembered that shear strength gain shown in Fig. 13 consists of components of secondary compression and cementation. To detect the effect of the cementation part alone, we have to amend the measured data by subtracting the part attri-
Fig. 13. Shear strength versus consolidation time (obtained by fall cone test)

Fig. 14. Relation between shear strength and water content

Fig. 15. Corrected shear strength in consideration of variation in water content

The relationship is expressed by Eq. (8), and it is conceivable that the scatters include alteration of consolidation duration and experimental error as well.

$$w = 144.4 - 32.85 \log (c_u)$$ (8)

With the help of the relation above, the effect of secondary compression on shear strength was eliminated in terms of discrepancy in water content.

$$\Delta w = -14.3 \frac{\Delta c_u}{c_u}$$ (8')

Averaged water content $\bar{w}$ is obtained for each group of the same consolidation pressure. Measured data shown in Fig. 13 were adjusted to equivalent shear strengths if water contents were equal to the averaged value $\bar{w}$. For example, if shear strength $c_u$ and water content $w$ were obtained for a given sample, then corrected shear strength was calculated by $c_u' = c_u + 14.3(w - \bar{w})$.

Figure 15 shows the corrected shear strength, in which shear strength gain from volumetric compression during secondary process is regarded as removed. Therefore, the increasing rate of shear strength in Fig. 15 is attributed to cementation only. Assessing directly the results in Fig. 15, we can obtain the increasing rate $\Delta c_u/\Delta \log t = 0.43, 0.86, 1.34$ kPa per log circle time approximately, for $p_0 = 2, 5$ and 10 kPa.

Consolidation with Large Oedometer

In addition to the consolidation experiment stated above, a kind of consolidation was conducted with a special large scale oedometer, as shown in Fig. 16. A vessel of 30 cm in diameter was used in this case. The material used was also Honmoku clay with initial water content of 170%. Clay slurry was poured into the consolidation vessel from a height of 15 cm. The clay slurry was enclosed and a small pressure of about 8 kPa was applied on it in the vertical direction. Pore water was allowed to drain from the upper and lower sides vertically, and from the center and periphery horizontally. Figure 17 shows settlement measured during the whole experiment procedure. It can be seen that the primary consolidation finished at around 1000 minutes.

The large oedometer was modified so that shear strength could be measured with a vane test device without unloading consolidation pressure or interrupting the secondary consolidation. Arrows in Fig. 17 denote the times when vane shear tests were performed. In fact the positions at which vane shear tests were conducted were around a certain radius, separated from each other. Figure 18 shows shearing resistance against rotating angle of vane plate (width 2 cm, height 4 cm, rotating rate 6 deg./min). It is clear that shear strength gain during the secondary process is fairly significant. Actually shear strength increased by 70% for the period of 2–21 days.
Figure 19 gives increasing relation of shear strength with elapsed time, as is shown by the solid line. The increasing rate of shear strength \( \Delta c_v / \Delta \log t \) is estimated at about 2.23 kPa per log circle of time. Here it should be remembered that such a value of increase includes both effects of secondary compression and cementation. To evaluate the cementation alone, we have to subtract the part of secondary compression. Based on settlement information shown in Fig. 17, this procedure was followed. The corrected shear strength is presented also in Fig. 19 with a broken line. The increase rate \( (\Delta c_v / \Delta \log t) \) due to cementation turns out to be 0.97 kPa per log circle of time.

**SHEAR STRENGTH GAIN UNDER PRACTICAL PRESSURES**

Some researchers have investigated the characteristics of increase of shear strength during the secondary process at pressure levels below those practically used. By practical pressures we mean \( p_0 = 50-1000 \) kPa.

Mitachi et al. (1987) carried out long term consolidation experiments on Hayakita and Ohnegai clays with triaxial apparatus. Information for the two clays is given in Table 2. Investigation by Mitachi et al. showed a rate of increase of shear strength normalized with consolidation pressure \( p_0 \), \( (\Delta c_v / p_0)_{sc} / \Delta \log t \), during the sec-

Fig. 18. Vane shearing tests conducted during secondary consolidation

Fig. 19. Increase of shear strength with elapsed time for the same sample

Fig. 17. Settlement for the large sample observed during entire experiment procedures
ondary process of about 0.044 for Hayakita clay, and 0.016 for Ohnegai clay. Similarly, the authors think such values consist of effects of secondary compression and cementation. The part attributed to secondary compression can be estimated by the relation of Eq. (1) with $\beta=1.0$. Immediately there results in the part from cementation, $(\Delta c_s/p_0)_sc/\Delta \log t=0.017$ for Hayakita clay, and barely is estimated for Ohnegai clay. It seems that, as pressure $p_0$ raises up to a practical level, the component attributed to secondary compression becomes outstanding and the component by cementation is no more. Sometimes it may be hard to detect the cementation effect (such as Ohnegai clay in Table 2).

In order to verify the validity of Eq. (1), Yasuhara and Ue (1983) carried out a series of direct shear tests under constant volume condition on Ariake clay ($w_i=115\%$, $L_p=58$). The authors analyzed the experimental data, and the results are presented in Table 2. It can be seen that the rate of increase of shear strength $(\Delta c_s/p_0)/\Delta \log t$, due to cementation is about 0.023 and 0.021 when $p_0=106$ and 212 kPa for Ariake clay (based on direct shear tests).

Recently, Ue et al. (1997) also conducted a series of consolidated undrained tests on Okayama clay ($w_i=77\%$, $L_p=48$), similar to the experiments by Mitachi et al. Table 3 presents increases in consolidation yield pressure $p_c$ and undrained shear strength $c_u$ obtained during the secondary process. The $c_u$ value predicted in the table is calculated according to the relation of Eq. (1). The effect of cementation evaluated for the case of 1 day's duration resulted in a minus value in Table 3. Most likely, this is because of experimental errors. There is also the possibility that soil parameters determined for Okayama clay made Eq. (1) overestimate slightly the component due to secondary compression. Based on the result in Table 3, though available data are not sufficient, an increase rate of $(\Delta c_s/p_0)/\Delta \log t=0.013$ was obtained for shear strength gain due to cementation during the secondary process.

Mesri suggested that the hardening effect in clay may be expressed with Eq. (3). Hereby, the first term in the right hand side of Eq. (3) is interpreted to be the cementation effect, and the second term is due to secondary compression. Assuming the ratio of strength increase $(c_s/p_0)_sc$ is about 0.3 for usual clays, the increase rate of shear strength due to cementation can be estimated from the first term directly. Estimation from Eq. (3) with $\beta=0.02$ gives $(\Delta c_s/p_0)/\Delta \log t=0.014$ when consolidation pressure varying within $p_0=100-800$ kPa.

### Table 2. Correction of shear strength gain during secondary process, $(\Delta c_s/p_0)_sc/\Delta \log t$

<table>
<thead>
<tr>
<th>Clay</th>
<th>$(c_u/p_0)_sc$</th>
<th>$C_s$</th>
<th>$C_u$</th>
<th>$A$</th>
<th>$p_0$ (kPa)</th>
<th>Rate of shear strength gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hayakita</td>
<td>0.335</td>
<td>0.31</td>
<td>0.065</td>
<td>0.010</td>
<td>0.81</td>
<td>600</td>
</tr>
<tr>
<td>Ohnegai</td>
<td>0.315</td>
<td>0.53</td>
<td>0.11</td>
<td>0.012</td>
<td>0.73</td>
<td>545</td>
</tr>
<tr>
<td>Ariake</td>
<td>0.35</td>
<td>0.838</td>
<td>0.157</td>
<td>0.031</td>
<td>0.685</td>
<td>106</td>
</tr>
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</table>

#### Table 3. Shear strength gain during secondary process (based on Ue et al., $p_0=196$ kPa)

<table>
<thead>
<tr>
<th>Secondary duration</th>
<th>Quasi-OCR</th>
<th>Measured $c_u$ (kPa)</th>
<th>Predicted $c_u$ (kPa)</th>
<th>Cementation $\Delta c_u$ (kPa)</th>
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<tr>
<td>4 hours</td>
<td>1.00</td>
<td>73.1</td>
<td>73.1</td>
<td>0</td>
</tr>
<tr>
<td>1 day</td>
<td>1.13</td>
<td>77.6</td>
<td>78.7</td>
<td>-1.1</td>
</tr>
<tr>
<td>3 days</td>
<td>1.21</td>
<td>87.5</td>
<td>82.4</td>
<td>5.1</td>
</tr>
<tr>
<td>7 days</td>
<td>1.28</td>
<td>93.6</td>
<td>85.4</td>
<td>8.2</td>
</tr>
</tbody>
</table>

### EXTENDING TO TINY PRESSURES

By tiny pressure here, we mean that overburdened pressure ranging within $p_0=0.01-0.1$ kPa. At such a small pressure level, the situation becomes more complicated and it is seen as hard to detect shear strength or pressure through usual procedures.

Zreik et al. (1997) conducted an experimental program on Boston blue clay ($w_i=43\%$, $L_p=20$, $w_0=550\%$). Their work was focused on the mechanical properties of clay at ultra-low stresses. In order to detect the tiny shear strength for the sedimentary sample, they designed an automated fall cone device, which is able to measure shear strength of $c_u=0.01-0.12$ kPa. In their experiments, clay slurry prepared from oven dried powder was set to sedimentation and consolidation under self-weight. As consolidation was completed, shear strength and water content were measured layer by layer at every 1 cm in thickness.

Figure 20 gives shear strengths by use of the special fall cone device, arranged in a manner similar to Fig. 7. It can be confirmed that shear strength increased remarkably for the duration from 3 days to 6 days. Meanwhile, Zreik et al. reported that changes in water content were insignificant. Evaluating from Fig. 20, the increase rate of shear strength is tentatively obtained as $(\Delta c_u/p_0)/\Delta \log t=1.62, 0.777, 0.485, 0.345$ and $0.310$ per log circle of time for $p_0=0.02, 0.05, 0.1, 0.2$ and 0.3 kPa.

### DISCUSSION

All the data available as examined above are given in Fig. 21, which is built on the basis of Fig. 11 by extending the scope of overburdened pressure $p_0$. It is worth emphasizing that the increase rate of shear strength in Fig. 21 is related to the strength gain attributed to cementation, not including the component associated with sec-
second compression (reduction of water content).

Except in the case of Ohnegai clay, the simple relation by Eq. (6) holds almost valid for the wide wild pressure range of \( p_o = 0.01\text{--}1000 \) kPa. The data based on studies by Zreik et al. (1997) and by Ue et al. (1997) seem somewhat smaller than the other data.

It is supposed from Fig. 21 that the contribution of cementation dominates strength gain with time if the overburdened pressure is smaller than the level of 100 kPa. Otherwise, strength gain due to secondary compression becomes the outstanding component when the overburdened pressure is larger than the level of 100 kPa.

CONCLUSIONS

The present study may be concluded as follow:

1) A concept has been introduced to evaluate the strength gain during the secondary process. It is suggested that strength gain with time could be characterized into components, one of which is associated with volumetric compression, while the other is attributed to the effect of cementation.

2) Special attention was focused on the component of strength gain attributed to the effect of cementation during the secondary process. Sedimentation and consolidation under self-weight, and consolidation under small pressure were performed, and the component of cementation was evaluated. It was found that the increase rate of shear strength, \( (\Delta c_u/\Delta \log t) \), depends on the overburdened pressure \( p_o \), as expressed by \( \Delta c_u/\Delta \log t = 0.3\sqrt{p_o} \). Back analyses of the data obtained by some researchers showed that this simple relation is valid for much wider range of pressure level as \( p_o = 0.01\text{--}1000 \) kPa.

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NOTATIONS

\( C_d \), coefficient of secondary compression
\( d \), penetration of fall cone
\( k \), coefficient of fall cone
\( p_{ov} \), overburdened pressure
\( p_y \), consolidation yield pressure
\( p_c \), pressure of \( e \)-log \( p \) curve crossing with instant curve
\( t_f \), ending time of primary consolidation
\( w_0 \), initial water content
\( \beta \), parameter of cementation effect (Muragami)
\( \beta \), parameter defining thixotropic hardening (Mesri)
\( A \), exponential index of shear strength for overconsolidated clay
\( \log \), common logarithm
\( EOP \), end of primary consolidation
\( OCR \), overconsolidation ratio
\( (C_d/p_0)_{BC} \), ratio of shear strength increase for normal consolidated young clay

REFERENCES