EFFECT OF AGING OF MARINE CLAY AND ITS DUPLICATION BY HIGH TEMPERATURE CONSOLIDATION

TAKASHI TSUCHIDA, MASAKI KOBA YASHI and JUN-ICHI MIZUKAMI

ABSTRACT

By comparing the behavior of undisturbed clay samples with that of remolded samples, the effect of aging on the mechanical properties of marine clays was discussed. The compression index $C_v$ and the secondary compression index $C_s$ of natural aged clays show peak values when the consolidation pressure is slightly larger than the consolidation yield stress. The compression index ratio $r_{cs}$, which is newly introduced in this study, is considered to be a useful index to represent the aging effect of natural clays. The values of $r_{cs}$ of Japanese alluvial clays range from 1.0 to 3.0 and they are smaller than those of East Canadian clays which are well-known as an aged clay. By consolidating clay slurry at a high temperature and cooling it after the completion of consolidation, remolded clay samples, whose mechanical properties are similar to those of lightly aged clay, can be produced in laboratory. The main cause of the effect of the high temperature consolidation seems to be the acceleration of cementation action. This procedure is useful to simulate the behavior of natural clay using laboratory tests of the remolded clays.

Key words: clay, compression, consolidation, laboratory test, soil structure, stress-strain curve, temperature effect, time effect (IGC: D5/D6)

INTRODUCTION

Mechanical properties of clay have been one of the most important subjects in soil mechanics. To investigate this subject, remolded and reconsolidated clays are frequently used in order to avoid the scatter of experimental results of natural clays. However, it was clarified that mechanical properties of remolded clays are quite different from those of natural clays; natural clays possess a structure formed due to various phenomena such as long term secondary compression and/or cementation effects (Tavenas and Leroueil (1977), Jamiołkowski et al. (1985)) Although these differences are most remarkable in diluvial clays, even alluvial clays have such a structure as never observed in remolded clays. Thus, laboratory testing results of remolded clay may lead to erroneous conclusions.

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Remolded clays are also used frequently in model tests such as centrifuge tests which have become very popular recently. However, modes of deformation and/or failure in the model tests may be quite different from those of the field because remolded clays poorly simulate natural clays. Thus, it is necessary to duplicate a clay structure in laboratory for both element tests and model tests.

In the previous works, chemical agents were used to get structured clays. The long term consolidation in a triaxial cell has been also conducted in order to study the effects of aging on the stress-deformation characteristics of clay. In this study, we propose a simple method in which clay slurry is consolidated at a high temperature and cooled at a room temperature after the completion of the consolidation. This idea comes from the fact that high temperatures may accelerate chemical actions in clay particles.

In this paper, mechanical properties of aged clay are firstly reviewed. Subsequently the properties of natural marine clays in Japan are compared with those of remolded clays. The compression index ratio $\tau_C$ is newly introduced to represent the aging effect of natural clays. Finally, by the results of consolidation tests, unconfined compression tests and triaxial tests, it is demonstrated that the use of high temperature consolidation has simple and yet powerful capabilities to duplicate a natural clay structure in laboratory.

**REVIEW OF PREVIOUS STUDIES**

Bjerrum (1967, 1973) firstly pointed out the importance of the aging effect on mechanical properties of soft clay deposit. Fig. 1 shows a schematic $e$–log $p$ relationship for aged clay which is proposed by Bjerrum. In this figure, the difference between young clay and aged clay is explained by the secondary consolidation or delayed consolidation i.e.; the aged clay is characterized by the increase of consolidation yield stress $p_C$ and the decrease of void ratio due to the secondary consolidation.

Another type of the difference in $e$–log $p$ curve is frequently seen between undisturbed samples of natural aged clay and remolded young clay. As shown in Fig. 2, $e$–log $p$ curve has a sharp bend and the virgin compression curve concaves downward for natural aged clay, while young clay has a gentle $e$–log $p$ curve.

Mesri and Godlewski (1977) investigated one dimensional compressibility of clay in detail. Fig. 3 reproduces their experimental results of Leda clay which is well-known as a cemented clay. In this figure, the compression index $C_e$ (defined as $\Delta e / \Delta (\log p)$) and coefficient of secondary compression $C_a$ (defined
clay becomes ductile because the clay structure having been formed by aging effect is destructed by the consolidation under the pressure far over the $p_e$.

Kamon and Nagao (1986) examined the mechanical properties of artificially cemented clays which were made by mixing portland cement or sodium silicate by 5% in weight. According to their experiments, the artificially cemented clays showed larger $p_e$, larger compressibility at the consolidation pressure over $p_e$ and larger undrained strength in the over-consolidation region than those of non-cemented clay.

Effect of consolidation duration on the undrained behavior had been studied by Bjerrum and Lo (1963), Yamaguchi et al. (1983), Yasuhara et al. (1985) and Mitachi and Fujiwara (1987). Among them, Mitachi and Fujiwara investigated the influence of duration of anisotropic consolidation up to 120 days, and reported that the initial modulus of deformation and the undrained strength increase with time of consolidation.

Summarizing the previous studies, two causes have been focused on as the aging effect. One is the secondary or delayed consolidation, the other is the cementation. According to the results of the experiments by Plum and Eserg (1969), the secondary consolidation seems to be accelerated under high temperature (Mitchell, 1976). If the cementation is due to the chemical action of a fine layer on clay particles (Bjerrum, 1973), the cementation will also take place in the shorter period under high temperature conditions because chemical action is more active. Therefore, it is considered that the consolidation of clay slurry under a high temperature will be useful to duplicate the effect of aging on mechanical properties of clays.

**MECHANICAL PROPERTIES OF NATURAL MARINE CLAYS IN JAPAN**

Firstly the compression and the shear behavior of Japanese natural marine clays were compared with those of remolded clays. In Fig. 4 is shown the compression index $C_c$ of both undisturbed and remolded marine clays.
As shown in this figure, the $C_e$ of undisturbed samples has a clear peak value when the consolidation pressure $p$ is 1.5~2.0 times of $p_0$, while $C_e$ of remolded samples is almost constant in the normally consolidation region. When $p$ is 3~5 times of $p_0$, undisturbed samples show constant values of $C_e$, which is same as those of remolded samples. This compression characteristics is similar to Fig. 3 reported by Mesri and Godlewski. Assuming that the difference shown in Fig. 4 between undisturbed clays and remolded clays is due to the aging effect of both samples, compression index ratio $r_e$ is newly defined in this study by the following equation and Fig. 5:

$$r_e = \frac{C_{e\text{ max}}}{C_e^*}$$

(1)

where, $C_{e\text{ max}}$ is the peak value of $C_e$ in Fig. 3 or Fig. 4, and $C_e^*$ is the $C_e$ at which consolidation pressure is five times of $p_{ce\text{ max}}$ ($p_{ce\text{ max}}$ is the consolidation pressure when $C_e = C_{e\text{ max}}$). As shown in Fig. 5, $C_e^*$ is the value when $C_e$ becomes almost constant, and $r_e$ shows the change of the compressibility of clay in the normally consolidation region.

Compression index ratio $r_e$ of 2 types of alluvial marine clays were calculated with $e$--log $p$ curves obtained by conventional consolidation tests of undisturbed samples. Fig. 6 (a), (b) and (c) show the relations between $r_e$ and plasticity index $I_p$, initial void ratio $e_0$, and compression index ratio $r_e$, respectively.
Fig. 6(c). Relationship between $r_e$ and clay content $f_c$ (Alluvial marine clays)

Fig. 7. Compression index ratio $r_e$ with the depth (Tokyo Bay Clay)

Fig. 8. Compression index ratio $r_e$ with the depth (Osaka Bay Clay)

with those of remolded samples, the following values of $r_e$ were obtained for both samples,

$r_e = 1.2-3.0$ (natural alluvial clays)

$r_e = 1.0-1.2$ (remolded clays)

Fig. 7 shows the change of $r_e$ of undisturbed Tokyo Bay samples with the depth. It is shown that the $r_e$ increases with the depth. Fig. 8 shows $r_e$ with the depth at a site in Osaka Bay, where the reclamation work after the installation of sand drains has been undertaken. Soil investigations were carried out before the installation of the drains and during the reclamation. The values of $r_e$ were obtained by the results of consolidation tests of both investigations. As shown in Fig. 8, $r_e$ of Osaka Bay clay increased with the depth, ranging from 1.1 to 2.5, before the installation of sand drains. However, during the consolidation with the reclamation work, the $r_e$ became almost constant value near 1.0.

Fig. 7 and Fig. 8 suggest that the compression index ratio $r_e$ represents the degree of aging of clayey ground and that $r_e$ increases with the depth in the naturally sedimented ground, while $r_e$ reduces to 1.0 in the consolidating young ground.

The $r_e$ of very deep diluvial clays was also
Fig. 9. Summary of index tests of Osaka Diluvial Clay

![Graph showing gradation, water content, liquid limit, plastic limit, plasticity index, and liquidity index with depth](image)

Fig. 10. Consolidation yield stress with the depth in Osaka Bay

![Graph showing consolidation yield stress (p) with depth](image)

Fig. 11. $r_e$ with the depth (Osaka Bay)

![Graph showing $r_e$ vs. depth for Osaka Bay Clay](image)

The values of $r_e$ were calculated by using $e$-$\log p$ curves of the diluvial clay samples. Fig. 11 shows the $r_e$ with depth. As shown in this figure, $r_e$ increases with depth up to 250 m depth, while in the samples deeper than 250 m, $r_e$ is almost constant. Fig. 12(a), (b) and (c) show the relations between $r_e$ and $I_p$, $e_0$, $f_0$, respectively. Although there exist large variations, $r_e$ of diluvial clay in Osaka Bay has the positive correlations with $I_p$, $e_0$ and $f_0$, as well as that of alluvial clays shown in Fig. 6. The reason for the differences of the $r_e$-depth relations in Fig. 11 seems to be due to the lower plasticity of clays deeper than 250 m. Fig. 11 also suggests that the compression index ratio $r_e$ increases with the...
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Fig. 12(a). Relationship between $r_e$ and plasticity index $I_p$ (Diluvial clay in Osaka Bay Clay)

Fig. 12(b). Relationship between $r_e$ and initial void ratio $e_0$ (Osaka Bay Clay)

Fig. 12(c). Relationship between $r_e$ and clay content $r_c$ (Diluvial clay in Osaka Bay)

Fig. 13(a). Stress-strain relationship in triaxial compression test (Alluvial clay in Osaka Bay, $r_e=1.3$)

The data of the previously published papers. The followings are the summaries of the values of $r_e$:

$r_e=1.1 \sim 3.0$ (Japanese Alluvial Marine Clays)
$r_e=1.1 \sim 6.0$ (Osaka Bay Diluvial Clays)
$r_e=3.2$ (Mexico City Clay after Mesri and Godlewski, 1977) after $r_e=4.2$ (Canadian marine clay, Jamiołkowski et al., 1983)
$r_e=6.0$ (Leda Clay, after Mesri and Godlewski, 1977)

In Japanese marine clays studied herein, the deep diluvial clays in Osaka Bay showed the largest $r_e$ value, which is as large as that of Leda clay. However, the values of $r_e$ of Japanese alluvial clays were smaller than those of Canadian clays which are well-known as aged clay.

The effect of the aging is also seen in the shear behavior. Undrained triaxial compression tests of undisturbed samples were carried out after the isotropic consolidation. Fig. 13 (a), (b), (c) and (d) show the stress–strain depth in the naturally sedimented ground when the plasticity is uniform.

The values of $r_e$ of Mexico City Clay and Canadian clays were also calculated by using
Fig. 13(b). Stress-strain relationship in triaxial compression test (Diluvial clay in Osaka Bay, $r_c=2.2$)

Fig. 13(d). Stress-strain relationship in triaxial compression test (Diluvial clay in Osaka Bay, $r_c=4.0$)

Fig. 13(c). Stress-strain relationship in triaxial compression test (Diluvial clay in Osaka Bay, $r_c=3.0$)

relations of undisturbed Osaka Bay clays whose values of $r_c$ are 1.3, 2.2, 3.0 and 4.0, respectively. The stress-strain relation of remolded Osaka Bay clay ($r_c=1.1$) is also shown in Fig. 13(e). In these figures, the $\sigma'_c/\sigma_c$ is effective consolidation pressure, and $\sigma'_c/\sigma_c$ is consolidation pressure normalized by the consolidation yield stress. As shown in these figures, the shear behavior of Osaka Bay clays had similar characteristics to that of Canadian clay reported by Jamiołkowski et al. (1985), i.e. undisturbed clays with large $r_c$ showed brittle behavior, while remolded clay showed ductile behavior.

Looking over Fig. 13, the following two points are considered as characteristics of aged clays:

a. Small strain at failure in overconsolidation region.
b. Sharp reduction of the strength after failure in overconsolidation region.

In order to represent the character b mentioned above, the parameter $s_\tau$ is defined as
more brittle behavior. Considering these test results, it seems that the compression index ratio \( r_e \) is effective as a parameter representing the effect of aging not only in the compression behavior but also in the shear behavior.

**RECONSOLIDATION OF CLAY AT HIGH TEMPERATURE**

The procedure for reproducing the structure of aged clay in laboratory, which is newly proposed in this study, is to prepare a sample by consolidating clay slurry at high temperature.

In order to prepare reconsolidated sample, disturbed marine clay (\( w_L=79\% \), \( w_F=37\% \)) was taken at Tokyo Bay. Firstly the clay was thoroughly remolded at a water content of 200%. After deairing for 48 hours, the slurry was put into a 20 cm diameter consolidation cell and consolidated one dimensionally. The consolidation cell was surrounded by hot water whose temperature was controlled at 75°C by an electric heater as shown in Fig. 15. Clay was first consolidated under the weight of the loading plate and four incremental pressures (10, 20, 40, 100 kPa) were applied subsequently by the air cylinder. After the completion of consolidation under the final pressure, the sample was unloaded and cooled at the room temperature (25°C). For comparison, clay sample consolidated using the same procedure but under the room temperature which is kept almost constant was also prepared.
Fig. 15. Apparatus for high temperature consolidation

Fig. 16. Time-settlement relationship during consolidation

Fig. 16 shows the typical time-settlement (expressed in void ratio e) relationships of both high temperature consolidation (HTC) sample and room temperature consolidation (RTC) sample for each pressure increment. The followings were observed in Fig. 16:

1) The settlement of HTC sample under the weight of the loading plate was smaller than that of RTC sample. However, under subsequent incremental pressures, the settlement of HTC sample was larger than that of RTC sample. Thus, the differences in the final void ratio of both samples were small.

2) It is clear that the consolidation is accelerated by use of high temperature.

The high temperature consolidation of Tokyo Bay clay was carried out three times. Table 1 shows the water content of each sample comparing with that of the room temperature sample. As shown in Table 1, although there exists some variation, the difference in water content between the HTC sample and the RTC sample could not be recognized clearly.

Table 2 shows the index properties of the HTC sample and the RTC sample. As shown in Table 2, the differences of both samples were almost negligible.

<table>
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<th>Room Temperature Consolidation</th>
<th>High Temperature Consolidation</th>
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<tbody>
<tr>
<td>Batch 1</td>
<td>77.2%</td>
<td>77.5%</td>
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<tr>
<td>Batch 2</td>
<td>86.7%</td>
<td>86.5%</td>
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<tr>
<td>Batch 3</td>
<td>75.2%</td>
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<tr>
<td>Average</td>
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<td>81.5%</td>
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Table 2. Index properties of high temperature consolidation sample and room temperature consolidation sample

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<tr>
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<tr>
<td>Clay (%)</td>
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<td>45</td>
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<tr>
<td>Silt (%)</td>
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<td>51</td>
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<td>Sand (%)</td>
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</tr>
<tr>
<td>Plastic Limit (%)</td>
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<td>33</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>78</td>
<td>80</td>
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<tr>
<td>Plasticity Index</td>
<td>46</td>
<td>47</td>
</tr>
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MECHANICAL PROPERTIES OF HIGH TEMPERATURE CONSOLIDATION SAMPLE

Conventional incremental oedometer tests for both HTC sample and RTC sample were carried out. Each load increment was maintained for two days. Fig. 17 shows $e$–log $p$ curves for both samples. For comparison, a result of undisturbed Tokyo Bay clay, whose
$p$ curve of the HTC sample can simulate that of the undisturbed alluvial clay which must have undergone aging for hundreds or thousands years. Thus, it appears that the procedure of high temperature consolidation is effective for reproducing the compression behavior of lightly aged alluvial clay.

The compressibility properties are compared in Figs. 18(a) and (b), where the compression index $C_e$ and the coefficient of secondary compression $C_s$ are plotted against the normalized consolidation pressure $p/p_c$, respectively. Here the value of $C_e$ was derived from the inclination of the last portion of $e$-$\log t$ curve. As shown in Figs. 18(a) and (b), both $C_e$ and $C_s$ have clear peaks in the vicinity of $p_c$ in HTC sample. Comparing Fig. 4 with Fig. 18, it is clear that the HTC sample behaves like aged clay and RTC sample behaves like remolded clay.

The following values of compression index ratio $r_e$ were obtained from Fig. 18:

\[
\begin{align*}
    r_e &= 1.0 \sim 1.1 \quad \text{(RTC sample)} \\
    r_e &= 1.9 \sim 2.1 \quad \text{(HTC sample)}
\end{align*}
\]

As far as $r_e$ is concerned, HTC sample showed almost same behavior as natural alluvial clays.

Table 3 shows the comparison of consolidation yield stress $p_c$. As shown in Table 3, the values of $p_c$ of HTC samples were 20% larger than those of RTC samples. This effect is considered to be a quasi-overconsolidation effect by the high temperature consolidation.

The shear behavior of both samples were compared by carrying out unconfined compression tests. Fig. 19 shows stress-strain curves of unconfined compression tests of HTC sample and RTC sample. Results of undisturbed clay are also shown in this figure for

<table>
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<th>Table 3. Comparison of consolidation yield stress</th>
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<tr>
<td>Room Temperature Consolidation</td>
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<tr>
<td>Test 1</td>
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<td>Test 3</td>
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consolidation yield stress is about 100 kPa, is also shown. As shown in this figure, $e$-$\log
Fig. 19. Stress-strain curve in unconfined compression test

Fig. 20. Strength and strain at failure in unconfined compression test

comparison. As shown in this figure, the HTC sample has clearer peak values of stress than the RTC sample. Fig. 20 compares strains at failure in the unconfined compression tests. In this figure, the unconfined compressive strength $q_u$ is plotted against $\varepsilon_f$. As shown in this figure, values of $\varepsilon_f$ of the HTC sample were almost the same as those of undisturbed clay while values of $\varepsilon_f$ of RTC sample were quite large. The unconfined compression strength of HTC sample were about 15% larger than that of RTC sample. The sensitivity $S_t$ of both samples were also quite different; $S_t=18$ for HTC sample and $S_t=7$ for

Fig. 21. Stress-strain relation in CIU triaxial test

Fig. 22. Stress-strain relation in CK$_s$U triaxial test
RTC. Comparing the results of both samples, it is clear that the shear behavior of HTC sample simulates that of undisturbed clay, i.e. brittle behavior.

Fig. 21 and Fig. 22 show the results of isotropically consolidated undrained triaxial tests (CIU tests) and $K_0$ consolidated undrained tests (CKU tests), respectively. In Fig. 21 and Fig. 22, the stress–strain curves are shown for various values of $\sigma_0'/p_0$ similarly to Fig. 13, where $\sigma_0'$=vertical consolidation stress and the deviator stress is normalized by $p_0$. As shown in Fig. 21 and Fig. 22, it is seen that the deviator stress of HTC samples have clear peak values at small strains for any consolidation pressures, while RTC samples don’t show peak values in the overconsolidated regions. The stress–strain behavior of HTC sample is similar to that of undisturbed samples having the large compression index ratio shown in Fig. 13.

Figs. 23(a) and (b) show the relation between strain and consolidation pressure of the constant stress ratio consolidation test, where consolidation pressure increased slowly with keeping the stress ratio $k=\sigma_a'/\sigma_l'$ ($\sigma_a'$=axial effective stress, $\sigma_l'$=lateral effective stress) constant. The test result of the undisturbed sample of Tokyo Bay clay is also shown for comparison. As shown in this figure, HTC samples and undisturbed samples clearly showed the yielding stress, where stress–strain relation changed remarkably, in any stress ratio. It is, however, rather difficult to find the yielding stresses in the test results of the RTC samples because the stress–strain relation does not show the sharp bend. Using the same procedure as Casagrande’s method for the determination of consolidation yield stress, the yield stresses were obtained for HTC samples and undisturbed samples. Fig. 24 shows the yielding surface, where the yield stresses are plotted in $p$–$q$ stress plane. As shown in this figure, HTC sample and undisturbed sample have the similar shape of the yield surfaces.

Thus, the results of triaxial tests demonstrate that the high temperature consolidation is a useful technique in duplicating clay structure in laboratory.
DISCUSSIONS

The results of the experiments have shown that the high temperature consolidation sample has mechanical properties similar to the natural aged clays. It was also found that compression index ratio \( r_e \) is an effective index to represent the effect of aging, and the following values for each sample were obtained.

\[ r_e = 1.2 \sim 3.0 \] (Undisturbed sample of alluvial marine clay)

\[ r_e = 1.0 \sim 1.1 \] (Room temperature sample)

\[ r_e = 1.9 \sim 2.1 \] (High temperature sample)

If the main cause of the aging is the secondary consolidation presented by Bjerrum's model (Fig. 1), the void ratio of aged clay should be smaller than that of young clay and the \( r_e \) of both clays should be the same because the secondary consolidation has no effect on the shape of \( e \)-log \( p \) curve in normally consolidation regions. In the present study, however, the void ratio of HTC sample was almost the same as that of RTC sample, and the increase of the \( r_e \) was found to be a unique characteristic of the aging effect.

The increase of \( r_e \) value is also observed in the consolidation tests on the artificially cemented clays, which was made by mixing a small amount of the cementing agent with clay slurry (Kamon and Nagao (1986)). According to Bjerrum (1973), the cementing agent, which exists as a uniform smear covering the surface of the mineral particles in clay, is the reason of the brittle behaviour of East Canadian cemented clays. The experimental results in this study can also be explained by considering that the strength of the chemical bonding (agent) between the mineral particles increased rapidly under high temperature conditions.

Based on the above considerations, it is concluded that the main cause of the aging effect observed in Japanese marine clays is the cementation and it can be duplicated by consolidating clay slurry in high temperature conditions. The high temperature consolidation has another advantage to shorten the consolidation duration or period as shown in Fig. 16. Therefore, the procedure presented in this study seems to be useful for carrying out laboratory soil tests and model tests, when one intends to simulate the behavior of natural clay using remolded clay.

CONCLUSIONS

The effect of aging on the mechanical properties of marine clays has been discussed, and a new procedure for reproducing the structures of aged clay in laboratory has been presented.

The conclusions obtained in this study are summarized as follows:

1) The compression index \( C_e \) and the secondary compression index \( C_a \) of natural aged clays have peak values when the consolidation pressure is slightly larger than the consolidation yield stress.

2) The compression index ratio \( r_e \), which is newly introduced in this study, is a useful index to represent the aging effect of natural clays.

3) The values of \( r_e \) of Japanese alluvial clays range from 1.0 to 3.0, which are smaller than those of East Canadian clays. The deep diluvial clays in Osaka Bay have larger values of \( r_e \) than the alluvial clays.

4) By consolidating clay slurry at a high temperature and cooling it after the completion of consolidation, remolded clay samples, whose mechanical properties are similar to that of lightly aged clay, can be produced easily in laboratory.

5) It is considered that the acceleration of the cementation action is the main cause of the effect of the high temperature consolidation.

6) The procedure proposed in this study seems to be useful for carrying out laboratory soil tests and model tests, when one intends to simulate the behavior of natural clay using remolded clay.

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