INFLUENCE OF CURING STRESS ON ONE-DIMENSIONAL YIELDING OF CEMENT-ADMIXED BANGKOK CLAY AT HIGH WATER CONTENT

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ABSTRACT

The influence of curing stress on the one-dimensional compression characteristics of cement-admixed clay at high water content is investigated by oedometer tests, with special attention paid to the primary vertical yield stress. From the test results, the stress acting during the formation of cementation plays an important role in the one-dimensional compression characteristics of cement admixed clay. The stress compresses the treated clay and results in an increase in the vertical yield stress. For the cement-admixed clay studied, the effect of the curing stress inherently reflects on the after-curing void ratio. Therefore, the primary vertical yield stress in one-dimensional compression is a function of the after-curing void ratio and the ratio of the clay water content to the cement content ratio.

Key words: cement, clay, curing stress, one-dimensional, yield stress (IGC: D5/M5)

INTRODUCTION

For decades, soil-cement columns (SCC) have been adopted for ground improvement, particularly in Thailand and other Southeast Asia countries. This technique is known for its ability to improve not only the shear strength but also the stiffness of the soils. The successful implementations with satisfactory long-term serviceability include the foundations of road embankments, taxiways and the runways of airports, and retaining structures (e.g., Broms, 1984; Bergado et al., 1999; Petchgate et al., 2007).

In practice, many mixing methods (e.g., Bruce and Bruce, 2003) are adopted to construct SCC. Among them, two most commonly used methods in Thailand are: 1) the jet-grouting method; and 2) the wet-process deep mechanical mixing method (DMM). This might be because experience with the construction of SCC over the years in Thailand has shown the outcomes of these two methods to be highly satisfactory. As a result, the water content of the soil treated by these two methods, particularly the jet grouting, is much higher than the value at the in-situ state and often higher than the liquid limit of the soil itself. For highly plastic clays, for example, Ariake clay and Bangkok clay, the water content values of natural clay before remolding were as high as in a range of 100–150 percent, respectively, as reported by Miura et al. (2001) and Lorenzo et al. (2006). This resulted in high values of void ratio of cement-admixed clay which are generally larger than 2.0 and, in some cases, as large as 5.0.

It is common knowledge that the shear strength and the deformation characteristics of soils can be improved when they are cemented. Therefore, it is of interest to evaluate the various effects on the yield vertical stress beyond which the vertical compressibility of cemented soil remarkably increases. Then, it will be possible to accurately evaluate the vertical yield stress of cemented soil for a given condition and the consequent vertical deformation when loaded under the design static working loads. Moreover, the yield stress is one of the key parameters for the development of many constitutive models. To this end, a large number of investigations have been performed to understand the behaviors and the factors affecting the yield stress of cemented soils in one-dimensional or triaxial compression. Over the past decade, a number of studies have been performed concerning the effects of stress applied during curing which are expected to play a role in the mechanical behaviors of cemented soils (e.g., Ahnberg, 2007; Ahnberg et al., 2001; Yamamoto et al., 2002; Rotta et al., 2003; Consoli et al., 2000, 2006). These studies demonstrated the importance of the acting stresses during the formation of the cement bonds on the behavior of cemented soils.

With a focus on cement-admixed clays used in soft ground improvement by wet-process DMM or jet grout-
Table 1. Index properties of natural Bangkok clay used in this study

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit, ( w_0 ) (%)</td>
<td>100</td>
</tr>
<tr>
<td>Plasticity index, ( I_p )</td>
<td>60</td>
</tr>
<tr>
<td>Water content, ( w ) (%)</td>
<td>84</td>
</tr>
<tr>
<td>Initial void ratio, ( e_o )</td>
<td>2.37</td>
</tr>
<tr>
<td>Specific gravity, ( G_s )</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Table 2. One-dimensional compression test program employed in this study

<table>
<thead>
<tr>
<th>Test no.</th>
<th>( w^* ) (%)</th>
<th>( C_w/A_w )</th>
<th>( C_o ) (%)</th>
<th>( A_w ) (%)</th>
<th>Curing period (day)</th>
<th>Curing stress (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>84</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2**</td>
<td>1.25 ( w_o )</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>130</td>
<td>10</td>
<td>144.4</td>
<td>14.4</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>4</td>
<td>130</td>
<td>15</td>
<td>139.3</td>
<td>9.3</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>5</td>
<td>130</td>
<td>20</td>
<td>136.8</td>
<td>6.8</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>6</td>
<td>160</td>
<td>10</td>
<td>177.8</td>
<td>17.8</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>7</td>
<td>160</td>
<td>15</td>
<td>171.4</td>
<td>11.4</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>8</td>
<td>160</td>
<td>20</td>
<td>168.4</td>
<td>8.4</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>9</td>
<td>200</td>
<td>10</td>
<td>222.2</td>
<td>22.2</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>15</td>
<td>214.3</td>
<td>14.3</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
<tr>
<td>11</td>
<td>200</td>
<td>20</td>
<td>210.5</td>
<td>10.5</td>
<td>28</td>
<td>0, 43, 86</td>
</tr>
</tbody>
</table>

* Test was performed on the undisturbed natural clay specimen
** Test was performed on the remolded clay at the water content which is 1.25 times the liquid limit without cement

It is therefore postulated as the at rest \( (K_0) \) condition. A curing vertical stress was successfully applied immediately to the target value by means of the oedometer apparatus. Using the porous stone disk that is well-fitted to the oedometer ring, the specimen loaded with a vertical curing stress was not squeezed out. Then, the applied stress during curing was removed just before the start of the one-dimensional compression test.

Specimens were initially prepared from the remolded soft Bangkok clay at different water content values of 130\%, 160\% and 200\% for simulating the actual mixing condition during SCC installation using mechanical mixing with either cement slurry or using the jet-grouting method. As the natural water content of soft Bangkok clay before remolding (Table 1) was smaller than these target values, additional water had to be added. The amount of additional water to be added to the natural clay so as to obtain the desired water content, \( w^* \), was determined as:

\[
\Delta W_o = \frac{W_o}{1 + \frac{w^*}{w_o}} (w^* - w_o)
\]

where \( \Delta W_o \) is the weight of additional water to be added;
$W_T$ is the total weight of natural clay before remolded; $w^*$ is the target water content after remolded (i.e., 130%, 160% and 200%); and $w_n$ is the water content of natural clay (84% for the studied clay). Then, the required additional water was added to the natural Bangkok clay and the contents were mixed together by a portable soil mixer for a few hours to obtain uniform remolded clay with a uniform water content. The remolded clay with water was kept in the container wrapped with layers of plastic film to avoid the loss of the water through drying. This wrapped container was stored in the temperature- and humidity-controlled room for one night, and then the water content was checked. Subsequently, the remolded clay was mixed again with cement slurry, prepared at the water-to-cement ratio ($w/c$) of 1.0, to preliminarily obtain cement-admixed clay paste. Then, additional cement slurry was added into the previously obtained cement-admixed clay paste at different designated cement contents (Table 2) and mixing continued.

Due to the inclusion of water in the cement slurry, the total water content of the cement-admixed clay paste at this moment is the summation of the water content of remolded clay before being mixed with cement slurry and the water content of the cement slurry. This total water content of the cement-admixed clay paste is hereinafter referred to as the "total clay water content ($C_w$)" and can be determined as:

$$C_w = w^* + (w/c)A_w$$

where $C_w$ is the total clay water content of the cement-admixed clay paste (%) reckoned from the dry weight of clay only; $w^*$ is the target water content after remolded (i.e., 130%, 160% and 200%); $w/c$ is the water-to-cement ratio (equal to 1.0 in the present study); and $A_w$ is the cement contents (%), defined as the ratio in percentage of the weight of cement to the dry weight of clay. In the present study, the ratios of the total clay water content to the cement content of the cement-admixed clay paste ($C_w/A_w$) for specified values of $w^*$ were controlled at 10, 15 and 20 (Table 2) as this parameter, $C_w/A_w$ is the strength-controlled parameter of the cement-admixed clay at high cement content (Miura et al., 2001; Horpibulsuk et al., 2005). Then, the cement contents, $A_w$, for different conditions of specimen were back-calculated by Eq. (2), as shown in Table 2, and used during the specimen preparation. Here, it is worth noting that $w/c$ stands for the water-to-cement ratio of the cement slurry while $C_w/A_w$ stands for the water-to-cement ratio of the cement-admixed clay paste.

**Specimen Preparations**

The oedometer ring is schematically shown in Fig. 1. It was modified from the original ring used in conventional oedometer tests by adding an upper ring to increase the specimen's height to account for large compression during curing with stress. According to the increased thickness of the specimen, the friction due to mobilization between the oedometer ring and the specimen was reduced by smearing silicone grease onto the inner periphery of the oedometer ring and then placing an encircled plastic sheet (Fang et al., 2004) on the smeared grease layer (Fig. 1). The top and bottom ends of the specimen were attached to porous stone discs to allow the uniform drainage of water.

Due to the high workability of the cement-admixed clay paste, a syringe was used to inject the paste into the oedometer ring to prepare the test specimen. All specimens from the same batch of the cement-admixed clay paste were prepared within 45 minutes to satisfy the workability when prepared by the syringe (Horpibulsuk et al., 2004). Then, the density of each specimen was determined, and only specimens with a smooth top surface were selected for testing. Subsequently, the selected specimens were cured under different stress values for 28 days. Finally, the density of each selected and cured specimen was determined again. At this stage, the density of specimens was found to be within a range of ±1%. In accordance with these careful quality controls, only one specimen was used for a testing condition. After the completion of the tests, the specific gravity, $G_s$, of all specimens was determined.

**TEST RESULTS AND DISCUSSIONS**

**Effects of Cement Inclusion**

Figure 2 compares the relationships between the void ratio in the arithmetic scale and the effective vertical stress in the logarithmic scale ($e - \log_{10} (\sigma_v)$ relation) among the untreated undisturbed and remolded clay specimens (test nos. 1 and 2 in Table 2) and the cement-admixed clay specimen at $w^* = 200\%$ and $C_w/A_w = 10$ (test no. 9 in Table 2, without curing stress). The test results from the untreated remolded clay were used to define the so-called "intrinsic compression line (ICL)". It can be seen that the one-dimensional yielding of untreated undisturbed clay exhibits on the right of the ICL have a yield vertical stress value beyond which the $e - \log_{10} (\sigma_v)$ relation moves toward ICL. This is due to the structure of the undisturbed clay, which is derived from a combination of fabric (the arrangement between the clay particles) and bonding (the force between these particles) (Mitchell, 1993). With this structure, the yield vertical stress is locat-
ed on the right of the ICL. Then, after the exhibited yielding, this structure is degraded, changing from a metastable to a stable condition, resulting in a convergence between the $e - \log_{10}(\sigma')$ relations of undisturbed and remolded clay (Baudet and Stallebrass, 2004). It should be noted that, in the present study, the yield vertical stress is defined as the value at which the relationship between the void ratio and effective vertical stress in full-arithmetic scale (i.e., $e - \sigma'$ relation) deviates from initial linear behavior (Rotta et al., 2003). The void ratio is derived from oedometer testing results together with the specific gravity and densities of specimens measured previously.

On the other hand, at the same value of $\sigma'$, cement-admixed clay shows a higher void ratio than the values of untreated clay due to the effects of structure additionally created by cement bonding. In addition, the yield vertical stress of cement-admixed clay is significantly higher than that of undisturbed clay (Fig. 2). Similar to undisturbed clay, the structure of cement-admixed clay is noticeably degraded after the yield vertical stress exhibited. However, the $e - \log_{10}(\sigma')$ relation of the cement-admixed clay at the post-yielding regime is still located on the right of the ICL, indicating that, at the same value of $\sigma'$, the void ratio of cement-admixed clay is always higher than the value of undisturbed clay. This can also be explained as a result of the existing fabric additionally created by cement bonding, similar to that in the framework proposed by Cotecchia and Chandler (2000).

**Effects of Curing Stress**

Figure 3 compares the $e - \log_{10}(\sigma')$ relations between cement-admixed clay at $w^* = 200\%$ and $C_w/A_w = 10$, cured without stress and cured at vertical stress values of 43 and 86 kPa (test no. 9 in Table 2, with curing stresses of 0, 43 and 86 kPa). It can be clearly seen that the curing void ratio (initial void ratio before testing) decreases with curing stress. In other words, curing stress compresses the treated clay. Consequently, the yield vertical stress increases as curing stress increases while the respective void ratio decreases. All yield vertical stress values as well as the void ratio values at yield and after curing condition (i.e., immediately before start of compression) for respective combinations of $w^*$, $C_w/A_w$ and curing stress are summarized in Table 3. In addition, Figs. 4(a), (b) and (c) respectively, show the influence of curing stress on the yield vertical stress for different values of $C_w/A_w$ and different $w^*$ equal to 130%, 160% and 200%. The following behaviors may be seen from Figs. 4(a)–(c):

1. For various $w^*$, the yield vertical stress noticeably decreases with increasing $C_w/A_w$. This implies that, under otherwise the same conditions, $C_w/A_w$ is a parameter controlling the yield vertical stress of cement-admixed clay. This behavior is consistent...
with many findings in past investigations (e.g., Miura et al., 2001; Horpibulsuk et al., 2004). In addition, the above-mentioned trend in behavior is also true for different curing stress conditions.

2. For the same $C_w/A_w$, the yield vertical stress noticeably decreases with an increase in $w^*$, showing that the amount of water largely affects the yield vertical stress of cement-admixed clay even though the cement content ($A_w$) increases with $w^*$ to keep $C_w/A_w$ the same as shown in Table 2 (e.g., for $C_w/A_w = 10$, $A_w = 14.4\%$, 17.8% and 22.2% respective for $w^* = 130\%$, 160% and 200%). In fact, the decrease in the yield vertical stress with increasing $w^*$ is consistent with the increase in the total clay water content ($C_w$; Table 2). Therefore, $C_w/A_w$ is a unique parameter for predicting the yield vertical stress of cement-admixed clay, but only when prepared under otherwise identical conditions. On the other hand, when $C_w/A_w$ is kept the same, the cement-admixed clay prepared with lower values of $C_w$ exhibits a higher yield vertical stress value. This finding is consistent with the test results discussed by Lorenzo and Berardo (2004). In fact, different yield vertical stresses for different $C_w/A_w$ and $C_w$ appear to be unique only when the void ratios are taken into consideration.

3. For different combinations of $w^*$ and $C_w/A_w$, the influence of the stress applied during curing on the increase of the yield vertical stress is very significant.

On the other hand, as clearly seen in Fig. 3, the $e - \log_{10}(\sigma_v)$ relations for the same $w^*$ and $C_w/A_w$ while different curing stresses tend to converge to a single line at the post-yielding regime. By investigating all the test results in the present study, it was found that this post-yielding compression line for a given combination of $w^*$ and $C_w/A_w$ is unique, irrespective of different curing stresses. This implies that the curing stress has no influence on post-yield fabric of cement admixed clay.

**Effects of $C_w/A_w$**

Figure 5(a) shows the relationships between the void ratio at yield ($e_y$) and the yield vertical stress ($\sigma_y$) in semi-logarithmic scale for cement-admixed clays for different combinations of $w^*$ and $C_w/A_w$ without curing stress. Similarly, Fig. 5(b) shows $e_y - \log_{10}(\sigma_y)$ relations for all test data. In addition, three different lines were reasonably fitted to data of the same $C_w/A_w$ irrespective of different $w^*$ and different curing stress conditions, as shown in Fig. 5(b). Then, Fig. 6 similarly shows the relationship between the “after curing void ratio, $e_a$” defined as the void ratio value determined after having finished the curing process before starting the one-dimensional compression test and the yield vertical stress. It should be noted here that a data point for $C_w/A_w = 20$ in Figs. 5(b) and 6 was omitted before linear regression as it was found that, when including this data point, its deviation from the best-fitted line significantly affects the trend line such that it does not truly reflect the real behavior. Furthermore, Table 3 also lists all the values of $e_y$, $\sigma_y$, and $e_a$ for all cement-admixed clay specimens prepared at different $w^*$ and different $C_w/A_w$ and are cured under different stresses. The following behaviors may be seen from Figs. 5 and 6:

1. For the same $C_w/A_w$, the different $e_y$; $\sigma_y$; $y$ yielding states are due to different $w^*$ and different curing stress conditions. On the other hand, different $e_y$; $\sigma_y$; $y$ yielding states for the same $C_w/A_w$ form a line or yield locus in $e:\log_{10}(\sigma_y)$ space.

2. Different lines or yield loci in $e:\log_{10}(\sigma_y)$ space for different $C_w/A_w$ are approximately parallel to each other and they are also parallel to ICL. This means that the characteristics of yield locus in $e:\log_{10}(\sigma_y)$ space are basically the same as that of ICL, among
Fig. 5. Influence of $C_w/A_w$ on the one-dimensional compression characteristics of cement-admixed clay: a) no curing stress and b) all test data

Fig. 6. Relationship between the after curing void ratio and the yield vertical stress

**CONCLUSIONS**

A series of special oedometer tests were carried out on cement-admixed clay prepared at different mixing ratios of cement to the water and different initial water content for remolded natural clay and cured under different vertical stresses. The study allows the following conclusions to be made:

1. The stress acting during the formation of cementation plays an important role in the one-dimensional characteristics of cement-admixed clay. It will compress the cement treated clay and results in increased vertical yield stress.

2. The post-yield compression behaviors of mixtures with the same mixing components converge on a single straight line on $e: \log_{10} (\sigma_v')$ space for a given $C_w/A_w$. Therefore, the yield vertical stress of cement-admixed clay in one-dimensional compression can be determined for a given $C_w/A_w$ value and $e_v$. However, in the same manner, the effect of curing stress inherently reflects to the after curing void ratio.

3. For the artificially cemented clay studied, the vertical yield stress in one-dimensional compression is a function of the curing void ratio and cement content (not $C_w/A_w$). However, in the same manner, the effect of curing stress inherently reflects to the after curing void ratio.

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