Strength behavior of cement-treated dredged clay with various sand content

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Dredged clay stabilized by cement has been widely utilized as a geomaterial. Intensive research has been conducted to understand its strength behavior. However, the influence of sand content on the mechanical behavior of cement-treated dredged clay has given less emphasis. The sand content of dredged clay is varied depending on the source. This study examined the correlation of various sand and cement content to the liquid limit and the strength behavior of dredged clay at a different curing period. It was found that to know the liquid limit after mixing with cement is useful to evaluate the liquidity or flow characteristics of cement treated clay. The liquid limit of cement-treated clay increased gradually up to 10% cement content and decreased at increasing cement content. The cement-water ratio can be used as a parameter to estimate the strength of cement-treated clay composed with different sand content. Even though various amount of sand was added to cement-treated clay, the strength seems to be not correlated with the sand content which is not more than 70%.

Key Words : marine dredged clay, strength development, cement/water ratio, liquid limit

1. INTRODUCTION

Dredged clay stabilized by cement has been predominantly used as a construction material, and intensive research has been conducted to understand its strength behavior. The relationship of Atterberg limits to the mechanical behavior of remolded soil has been an attractive topic to researchers. Chew et al. (2014) observed that the liquid limit and plastic limit of soil increased gradually at a lower cement content (≤10%) during 7 days and 28 days of curing period and then decreased by the addition of cement. This behavior was due to the microporous nature of the aggregated particles of the material that traps the water within intra-aggregate pores. On the other hand, according to Uddin et al. (1997), the changes in the liquid limit by adding cement to the soil was minor while the plastic limit was observed to improve by increased cement content and curing time.

Furthermore, researchers have been studying the strength of cement-treated clays and the factors that affect its behavior. Sasanian et al. (2014) studied the basic parameters governing the behavior of cement-treated clays and correlate the behavior with clay mineralogy. On the other hand, Tsuchida et al. (2014) proposed a formula to estimate the unconfined compressive strength of cement-treated clay and examine the fitness of the formula for six marine clays in Japan. The strength behavior of cement-treated clay during at early stages of curing was studied by Kang et al. (2016) and observed that the strength development of cement-treated marine clay could be divided into early stage (t<3days) and later stage (t>3days). Although, there have been numerous studies conducted on the behavior of cement treated clay, the effect of sand content to the strength behavior of cement-treated have given less emphasis.

This study examined the correlation of various sand content and cement content to the liquid limit and the strength behavior of cement-treated dredged clay at...
different curing period.

2. MATERIALS AND EXPERIMENT PROCEDURE

(1) Material

Tokuyama Clay and Toyoura sand are the soils used in this study and Ordinary Portland Cement (OPC) as the cementing agent. The physical properties of Tokuyama clay were shown in Table 1. The Atterberg limits of Tokuyama clay such as its Liquid Limit, Plastic Limit, and Plasticity Index were primary measured by Casagrande method. The obtained results specified that Tokuyama clay has a liquid limit and plastic limit of 95% and 37.6% respectively. The particle size distribution for Tokuyama clay and Toyoura sand were presented in Figure 1 where it shows that Tokuyama clay contains 19.3% of coarse-grained soils (>75μm) and 80.7% of fine-grained soils (<75μm). The X-ray diffraction result for Tokuyama clay was shown in Figure 2. Toyoura sand which has been a common material for laboratory experiments was added to the clay to investigate the effect of sand to the liquid limit and strength of cement treated clay. Ordinary Portland cement was the cementing agent in this study due to its availability, effectiveness and widely utilized in the soil improvement method.

(2) Sample preparation and experiment procedure

a) Liquid limit

In the practice of dredged clay for filling or reclamation in coastal areas, the dredged clay is mixed with cement slurry by the specially manufactured mixer and transported to the site through steel pipes by the squeeze pump. As the cement-treated soils are transported and placed to the construction site immediately after mixing, the mechanical properties of cement treated soil after the mixing is necessary for the construction quality control. In the present, the quality control of cement-treated soil after the mixing is carried out with the flow value measured by the flow test. In the previous practices for cement treated clays in the coastal areas, the flow value was controlled in the range between 100 to 180 mm depending on the construction condition. According to the technical manual of pre-mix vessels method (2013), for a long distance transporting of cement-treated soil by squeeze pump, the flow value must be more than 150 mm. Whereas to make a slope by placing cement-treated clays, the flow value should be 120-130 mm (Technical Manual of Pre-Mix Vessels Method, 2013). Figure 3 shows the relationship between the flow value and vane shear strength. As shown in Fig. 3, the flow value was correlated to the vane shear strength of clay slurry which is smaller than 1 kPa.

Knowing the liquid limit after mixing with cement is useful to evaluate the liquidity or flow characteristics of cement treated clay. The Casagrande and Fallcone method were used in this research to study the

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit, LL (%)</td>
<td>95</td>
</tr>
<tr>
<td>Plastic Limit, PL (%)</td>
<td>37.6</td>
</tr>
<tr>
<td>Ignition Loss, Li (%)</td>
<td>6.21</td>
</tr>
<tr>
<td>Particle Density, Gs (g/cm3)</td>
<td>2.64</td>
</tr>
<tr>
<td>Coarse-grained soil (%)</td>
<td>19.3</td>
</tr>
<tr>
<td>Fine-grained soil (%)</td>
<td>80.7</td>
</tr>
</tbody>
</table>

Table 1 Physical Properties of Tokuyama Clay

Fig. 1 Grain-size distribution curve for Tokuyama clay and Toyoura sand

Fig. 2 X-ray diffraction patterns of Tokuyama clay

Fig. 3 Relationship between flow value obtained by cylinder method and vane shear strength
relationship between the liquid limit and mechanical behavior of a remolded soil. The sample was prepared based on Japan Geotechnical Standard in carrying out the liquid limit test by the Casagrande and Fallcone method (JGS) except for the mixing of the sand. To attain the target sand content ($S^*$), which are 30%, 40% and 50% Toyoura sand was mixed into the Tokuyama clay that had passed through a 2mm sieve using a mechanical mixer for 10mins. The sample mixing proportions was summarized in Table 4. The sand content was determined by the ratio of the mass of sand to the mass of clay plus the mass of sand as shown in the equation (1).

$$S^* = \frac{m_{sand}}{m_{clay} + m_{sand}} \times 100$$

(1)

The cement hydration reaction initiates shortly after the mixing of water and will improve when there was a sudden change in the temperature. In cement-treated clay, the setting time due to chemical and hydration reaction could be delayed by lowering the temperature of the mixture (Kang et al. 2016). With this, the clay-sand mixture was cooled to 0-2°C before the addition of cement and the distilled water added during the carrying out of the liquid limit test was chilled to 0-2°C. The cement content, $c$ is commonly defined as follows,

$$c = \frac{m_{cement}}{m_{clay} + m_{sand}} \times 100$$

(2)

However, the cement content in this study was defined as the ratio of the mass of cement to the mass of solid particles in the cement, clay, and sand shown in Eq. (2).

$$c^* = \frac{m_{cement}}{m_{clay} + m_{sand} + m_{cement}} \times 100$$

(2)

The cement slurry added to the clay-sand mixture had a water cement ratio of 1:1 for all the samples.

### Table 4 Mixing proportion for liquid limit test

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sand Content (%)</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
<th>Cement content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19</td>
<td>94.96</td>
<td>37.63</td>
<td>0.10, 15, 20 and 30</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>84.32</td>
<td>35.02</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>38</td>
<td>72.11</td>
<td>27.50</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>58.76</td>
<td>24.68</td>
<td></td>
</tr>
</tbody>
</table>

(b) Strength test

Laboratory Vane Shear Test (LVST) and Unconfined Compression Test (UCT) were carried out to observe the behavior of strength in the addition of sand to cement treated clay at different curing time. LVST was used to observe the strength at the early curing time from 0.5 hours to 5 hours. On the other hand, UCT was carried out to the samples cured from 7 hours to 90 days. The equations (1) and (2) were also used to calculate the target sand and cement content. The sample’s mixing proportions were summarized in Table 5. The water content of all samples was initially set to 1.5 times the liquid limit after adding the cement, as shown in Eq. (3), to remove the effect of a change in moisture content after adding cement.

$$1.5W_c = \frac{m_{oem}}{m_{clay} + m_{sand} + m_{cement}}$$

(3)

The sample preparation was in accordance with the guidelines set by Japanese Geotechnical Society for stabilized soil specimens without compaction (JGS, 2015). The clay and distilled water were cooled to 0-2°C to delay the chemical and hydration reaction during the sample preparation. Cement milk was used for all of the samples having a water cement ratio of 1:1. Vacuum mixer was used to mix the sample for 30mins to prevent evaporation and chemical reaction (Kang et al.). Then the mixed sample was transferred to a vane shear and unconfined compression molder with dimensions 60mm x 60mm and 50mm x 100mm, respectively. Moderate

### Table 5 Mixing proportion for strength test

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sand Content (%)</th>
<th>Cement content (%)</th>
<th>Cement content (%)</th>
<th>Water content (%)</th>
<th>Wet density (g/cm³)</th>
<th>Curing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>19</td>
<td>10.0</td>
<td>11.1</td>
<td>141.69</td>
<td>1.351</td>
<td>0, 5, 2, 5, 7, 10, 15 (hours)</td>
</tr>
<tr>
<td>1-2</td>
<td>19</td>
<td>15.0</td>
<td>17.6</td>
<td>141.69</td>
<td>1.353</td>
<td>1, 2, 4, 7, 28, 90 (days)</td>
</tr>
<tr>
<td>1-3</td>
<td>19</td>
<td>20.0</td>
<td>25.0</td>
<td>141.69</td>
<td>1.355</td>
<td></td>
</tr>
<tr>
<td>2-1</td>
<td>27</td>
<td>10.0</td>
<td>11.1</td>
<td>126.48</td>
<td>1.383</td>
<td></td>
</tr>
<tr>
<td>2-2</td>
<td>27</td>
<td>15.0</td>
<td>17.6</td>
<td>126.48</td>
<td>1.386</td>
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<tr>
<td>2-3</td>
<td>27</td>
<td>20.0</td>
<td>25.0</td>
<td>126.48</td>
<td>1.389</td>
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</tr>
<tr>
<td>3-1</td>
<td>38</td>
<td>10.0</td>
<td>11.1</td>
<td>108.15</td>
<td>1.432</td>
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<tr>
<td>3-2</td>
<td>38</td>
<td>15.0</td>
<td>17.6</td>
<td>108.15</td>
<td>1.435</td>
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<tr>
<td>3-3</td>
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<td>20.0</td>
<td>25.0</td>
<td>108.15</td>
<td>1.438</td>
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</tr>
<tr>
<td>4-1</td>
<td>50</td>
<td>10.0</td>
<td>11.1</td>
<td>88.20</td>
<td>1.501</td>
<td></td>
</tr>
<tr>
<td>4-2</td>
<td>50</td>
<td>15.0</td>
<td>17.6</td>
<td>88.20</td>
<td>1.505</td>
<td></td>
</tr>
<tr>
<td>4-3</td>
<td>50</td>
<td>20.0</td>
<td>25.0</td>
<td>88.20</td>
<td>1.509</td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>70</td>
<td>10.0</td>
<td>11.1</td>
<td>59.85</td>
<td>1.649</td>
<td></td>
</tr>
<tr>
<td>5-2</td>
<td>70</td>
<td>15.0</td>
<td>17.6</td>
<td>59.85</td>
<td>1.654</td>
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<tr>
<td>5-3</td>
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<td>20.0</td>
<td>25.0</td>
<td>59.85</td>
<td>1.659</td>
<td></td>
</tr>
</tbody>
</table>
tapping was done to avoid the formation of air voids in the placing of sample mixture to the molds and then sealed using polyethylene wrap. The curing time was uniformly set to 30 mins after the mixing of the sample. The samples for LVST have cured under atmospheric pressure while underwater for UCT at 20°C room temperature.

(3) Laboratory Experiment Apparatus

a) Casagrande method and the fall cone method
Each country has a standard for laboratory experiment procedures and apparatus. In this study, the Casagrande method was based on JIS A 1205, whereas, the fall cone method was based on JGS 0142, wherein the conical angle and cone mass were 60° and 60g, respectively.

b) Laboratory vane shear test (LVST)
During the early stages of curing from 30 minutes to 5 hours, the sample was in the fragile stage, therefore, laboratory vane shear test was carried out. The LVST used in this experiment has a blade diameter and height of 20 mm and 10 mm, respectively and a vane shaft diameter of 2 mm. The rotation was uniformly set to 6° to 12° per minute.

c) Unconfined Compression Test (UCT)
The strength of the samples which were cured from 7 hours to 90 days was measured using the UCT. Following the Japanese Industrial Standards (JIS A 1216 (2008)), the strain rate used in this study was 1% per minute.

3. RESULT AND DISCUSSION

(1) Liquid limit of clay with sand and cement content
The liquid limit of soil is related to the mechanical behavior of remolded soil. According to JGS 0142-2009, the major factors affecting the consistency limits of the soils were particle size distributions, particle shapes, specific surface areas, mineral types and contents, the concentration of salts in the pore water, the intensity of particle surface charge, the thickness of absorbed water layer and the type of organic matter. However, the liquid limit of soil with different sand content and cement content were not fully examined.

Fig. 4 (a) and (b) show the comparison of liquid limits obtained from the percussion test and the fall cone test obtained by different penetration depths, 10mm penetration depth, LLc=LLFC(10) and 11.5mm penetration depth, LLc=LLFC(11.5). Having this result and owing to the easier operations of the fall cone method, in this study, the liquid limit of cement treated clay-sand mixtures was determined by fall cone test at 10 mm penetration depth.

Fig. 5 shows the relationship between the liquid limit and sand content at each cement content. The liquid limit decreased with an increase of sand content at each cement content used, and its relationship shows an approximately linear relationship. The gradient of linear line increased with a decrease of cement content excluding of the sample without cement.

Fig. 6 demonstrates the relationship between the liquid limit normalized by the value at no cement and the cement content at each sand content. The liquid limit on
all samples increased between $c^*=0$ and $c^*=10\%$ and then decreased with the increased of cement content. Hence, we suggested that cement can play two roles: 1) physico-chemical effect to electric double layer of aggregates or clusters in a mixture and 2) reduction of water content due to added cement particle. It was suggested that the physico-chemical effect reached the maximum within about 10% cement content and the effect of reduction of water content was dominant when the cement content increases more than 10\%.

(2) Effect of sand to the strength development

Fig. 7 and Fig. 8 shows the relationship of strength ($q_u$) to the curing time of all samples in log-log scale and semi-log scale respectively. As shown in the Fig. 7, the strength and curing time relationships were almost linear when the curing time is less than three (3) days and the Fig. 8, shows that the strength increased with the logarithm of curing time after three (3) days. These
relationships were also reported by Kang et al. (2014) for plastic marine clays. Therefore, the relationship of $q_u$ to curing time at log-log and semi-log scale of clay with various sand content was similar to the plastic marine clay.

Fig. 9 (a) and (b) shows the relationship between the strength and the sand contents when the cement content is at 10%. As shown in this figures, the mobilized strength was almost same at the early stage where the curing time is less than 1 day. The differences of strength were gradually improved at the later stage and at 90 days. The absolute increase in strength was observed when the sand contents were 50% and 70%. Fig. 10(a) and (b) and Fig. 11 (a) and (b) shows same relationships however the cement contents were 15% and 20%. In this figures, the effect of sand was not noticed in the early stage of curing, and the strength increase was seen at sand contents more than 50%.

Fig. 12(a) and (b) shows the relationship between strength and the cement-water ratio at 28 days and 90 days of curing period. It can be observed that the strength increase was observed when the sand contents were 50% and 70%. Fig. 10(a) and (b) and Fig. 11 (a) and (b) shows same relationships however the cement contents were 15% and 20%. In this figures, the effect of sand was not noticed in the early stage of curing, and the strength increase was seen at sand contents more than 50%.

4. CONCLUSIONS

From the result of series of experiment, the following conclusions were made:
1) To know the liquid limit after mixing with cement is useful to evaluate the liquidity or flow characteristics of cement treated clay.
2) The liquid limit of cement-treated clay with various sand contents increased gradually up to about 10% cement content and decreased with increasing cement content.
3) The strength and curing time relationships were almost linear when the curing time is less than three days at log-log scale then the strength increased with the logarithm of curing time after 3 days.
4) The cement-water ratio can be used as a parameter to estimate the strength of cement-treated clay with different sand content. Even though various amount of sand was added to the cement-treated clay, the strength seems to be not correlated with the sand content up to 70%.

REFERENCES