Introduction

In Japan, the coastal development for industrial and residential uses is one of the most important issues for economic growth. However, traditional reclamation materials such as dredged sand and crushed rock have hardly become available due to environmental concerns. On the other hand, the amount of dredged soil produced from maintenance of navigation channels, sewages and constructions are so large that it requires appropriate measures to manage it. Because the available places for disposing dredged soil are limited, the most preferable solution is to recycle it as reclamation material. However, natural properties of the dredged soil are unsuitable for such purposes, with high water content, high compressibility, and low strength. Proper understanding of such soils’ properties, both at natural and improved states, will lead to the supply of sustainable reclamation materials for the coastal and infrastructure development, imposing the minimum stress to the environment. Towards such fundamental understanding, suitable experimental testing methods and frameworks for interpretation have been implemented that serve to engineering practice as well as are academically novel. Generally, there are two ways of using dredged soils or very soft clays as fill material, i.e. stabilized with solidifier such as cement or directly applied to reclamation site. In the former method, dredged soils are commonly mixed with small percent of cement named as the Pipe Mixing or Super Geo-Material methods, which are widely used in the reclamation projects, have high water contents and behave as a liquid at the early stage. This liquidity property allows it to be transferred through a pipe from a mixing plant to the construction site; the distance usually is as long as 2 km. In these techniques, a method for controlling and monitoring the quality of treated material is essential. If the material is too stiff, the soil cannot be transported due to high resistance, while the beneficial properties such as eventual strength and stiffness are compromised by adding too much water. Both the water content and the cement ratio should therefore be carefully monitored and controlled so that they properly keep a balance between early-stage fluidity and strength at the later stage. Thus, the precise determination of stiffness and strength development during hardening process of the material would lead to a better understanding of its behavior. For the latter method, the ground can be improved by vertical drain, vacuum consolidation, or preloading, for example. At the first stage of construction, cover material needed to be spread on the top of the soft ground then followed by installation of heavy machineries, which requires the ground with adequate strength to stand. Therefore, the evaluation of underlying soil properties like the hardening stiffness and strength with time is very important. The mechanism is known as “Thixotropy Hardening” which simply in geotechnical engineering means after softening by remolding, the process of time-dependently return to harder state under constant water content or volume conditions.

In this thesis, the development of shear modulus and undrained shear strength of cement treated soil and very soft clays are measured by bender element tests and laboratory vane tests. The correlation of these two parameters is proposed.

Materials and Sample Preparations

To obtain the soil sample for experiments, commercial powder clays and natural clays have been used and its index properties are summarized in Table 1 for cement-treated soils and very soft clays. These soils are mixed with various water contents and cement contents in accordance with research purposes.

Both CTS and very soft clays were poured into a mold with various sizes for different purposes: a plastic cylindrical mold with the height of 10 cm and the diameter of 5 cm for the bender element test, a gallon bucket with 20 cm of the diameter for laboratory vane test. Vibration was gently applied to drive out air bubbles from a slurry specimen and a sample was compacted when its water content was small and the sample was stiff. The uniformity of the very soft clays’ samples was not well guaranteed for the latter case, i.e., inevitably the sample was partially unsaturated.

Table 1 Physical Property of Soil Samples for Very Soft Clays and Cement Treated Soils

<table>
<thead>
<tr>
<th>Testing Purposes</th>
<th>Soil Types</th>
<th>Plastic Limit (%)</th>
<th>Liquid Limit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very Soft Clays</strong></td>
<td>Fujinomori</td>
<td>21.3</td>
<td>48.6</td>
</tr>
<tr>
<td></td>
<td>Kasaoka</td>
<td>27.5</td>
<td>62.0</td>
</tr>
<tr>
<td></td>
<td>NSF</td>
<td>29.0</td>
<td>55.0</td>
</tr>
<tr>
<td></td>
<td>Ariake</td>
<td>31.4</td>
<td>72.5</td>
</tr>
<tr>
<td></td>
<td>Hachirogata</td>
<td>96.5</td>
<td>246.0</td>
</tr>
<tr>
<td></td>
<td>Tokuyama</td>
<td>40.0</td>
<td>110.6</td>
</tr>
<tr>
<td><strong>Cement Treated Soils</strong></td>
<td>Fujinomori</td>
<td>26.0</td>
<td>51.0</td>
</tr>
<tr>
<td></td>
<td>Kasaoka</td>
<td>28.0</td>
<td>62.0</td>
</tr>
<tr>
<td></td>
<td>Tokyo Bay</td>
<td>33.0</td>
<td>103.0</td>
</tr>
</tbody>
</table>
Testing methods

Bender element test

In this experiment, the soil specimen can be set up under unconfined condition and transmitter is placed on the top of the specimen, while receiver is set at the bottom. When the electric voltage is applied by function generator to transmitter element, it will bend and propagate shear wave signal through the specimen. The receiver element at the base is then bent by the arrival of the shear wave and generates a certain voltage. Input as well as received signals are displayed in a digital oscilloscope, such that the shear wave is identified and its velocity can be calculated using Eq. (1)

\[ V_s = \frac{\Delta d}{\Delta t} \]  

where \( \Delta d \) and \( \Delta t \) are travel distance and travel time of shear wave, respectively.

The Start-to-Start Method and Tip-to-Tip Method suggested by Viggiani and Atkinson (1995), Kawaguchi et al. (2001), and Yamashita et al. (2009) was adopted in this study to determine travel time and travel distance, respectively.

To obtain shear modulus \( (G) \), the formula can be derived from \( V_s \) through shear wave propagation in an elastic body theory as shown in Eq. (2)

\[ G = \rho \cdot V_s^2 \]  

where \( \rho \) is the density of the soil specimen.

Laboratory vane test

Because most of the soil samples concerned in the present study are very soft with low strength that conventional triaxial or unconfined tests cannot be performed, the vane shear test was an appropriate test. Undrained shear strength \( (s_u) \) is calculated by Eq. (3):

\[ s_u = \frac{2T}{\pi \cdot D^2 \cdot \left( H + \frac{D}{3} \right)} \]  

where \( T \) is the measured torque at peak, \( D \) is the vane diameter, and \( H \) is the vane height.

The vane diameter and height used in this experiment were 20 mm and 40 mm, respectively. The shear rate of the laboratory vane apparatus was constant at 6° rotations per minute.

Shear Wave Velocity and Shear Modulus By Bender Element Tests

Cement-Treated Soils

The plots in Fig. 1 show typical examples of the increase in the value of \( V_s \) with the curing time from the bender element tests. In the figure, Kasaoka clay was mixed to a water content of 80% and a cement content of 4%. In these tests, the voltage of the input pulse for both the sine and the rectangular waves was constant (±10 V); however, its frequency was varied to search for the optimum output signals to avoid any influences caused by undesired noises such as the near-field-effect (see Yamashita et al. 2009). Throughout the measurement process, frequencies of the input pulse were increased according to increases in the curing time or the soil stiffness. For the purpose of this study, the start of the curing time was defined as the time when the mixing had been completed and the mixed soil had been poured into the mould. Immediately after the mixing (approximately 10 min of curing time), no shear wave signal could be detected, as shown in Fig1. The fact that shear waves could not propagate through the liquid indicates that the specimen was still soft and in a “liquid” phase. After 30 min, a shear wave started to be observed, but its amplitude and frequency were low. The defined arrival time is represented by the symbol ▼ in Fig. 1; the \( V_s \) value is around 8.6 m/s at this time. As the curing time increased, the arrival time became shorter, in other words, the magnitude of \( V_s \) increased. Also, the wavelengths became shorter corresponding to the input signals.

Measurement of the shear modulus \( (G) \) was performed using bender element tests on a total of thirteen CTS samples. Seven samples were Fujinomori clay and the other six were Kasaoka clay. The Fujinomori clay was prepared at water contents ranging from 60% to 80%, while the Kasaoka clay was prepared at water contents ranging from 80 to 160%. The cement content varied from 4 to 10% for both clays.

The plots in Fig. 2(a) depict the variation in measured \( G \) with curing times for all thirteen samples. Generally, the \( G \) values are seen to increase with the curing time. However, some samples, for example, w:C = 60:4 and w:C = 70:4.7, showed an almost constant \( G \) value. Nonetheless, by using a log scale for \( G \), as presented in Fig. 2(b), a slight increase in \( G \) is identified because the bender element is quite sensitive and is able to detect even a small change in the material stiffness. From all the tests in this study, it was found that the minimum \( V_s \) detectable by the bender element tests was around 2.8 m/s, corresponding to a \( G \) of about 12 kPa. Looking at these figures, the development rate of \( G \) was apparently affected by many factors, including soil properties, the amount of water and the cement content. As expected, under the same water content, the samples (the same soil types) with a higher quantity of cement possessed a greater \( G \).

Very Soft Clays

Figure 3 shows an example of increase in the shear wave velocity \( (V_s) \) with time, measured by the bender element test on a specimen made from Kasaoka clay mixed with 60.6% of water content.

In this example, the input wave with 1 kHz of frequency and ±10 V of amplitude was adopted, as indicated on the top of the figure. Several waves at lowered figures are received signals with black triangles defining their arrival time. Since the water content of
the specimen was almost equal to liquid limit state, the received shear wave signals at the beginning of the measurement were hardly identified because of their low amplitude and frequency. P-waves clearly appeared since they could propagate through liquid. As time was proceeded, the soil became stiffer; consequently the arrival times were detected more shortly, in another word the shear wave velocity increased. It may be considered that the increase in $V_i$ corresponds to the increases in the stiffness, which is reflected to “the thixotropic phenomenon”. The received shear waves became much clearer with high amplitude and frequency after a certain time, while P-waves seemed to decay.

By conducting the same testing method on other soils under various water content conditions, the shear modulus ($G$) derived from $V_i$ with elapsed time is illustrated in Fig. 4. The symbols of A, F, K, N, H, and T represent Ariake, Fujinomori, Kasaoka, NSF, Hachirogata, and Tokuyama clays respectively with sample number. The number in the bracket indicates the water content ($w$) and the normalized water content by the liquid limit ($w/L_L$). It can be seen from the figures that $G$ values for all conditions increases with time even at over limit liquid states. And, $G$ builds up nearly in proportion to time in the logarithm scale, but this magnitude is certainly depended on types of soils and the amount of water content.

Since $G$ increases in time, $G$ at 24 hrs ($G_{24}$) will be a represented parameter for identifying characteristics of soil types and influence of water content. $G_{24}$ is plotted in Fig. 5(a) against the normalized $w/L_L$, considering different types of materials. A clear correlation between these two parameters can be observed with minor scatters. Obviously, $G$ decreases with increasing the normalized $w/L_L$, meaning that $L_L$ defines the magnitude of $G$ regardless types of soils. In this case, $G_{24}$ value at $L_L$ appears around 200 kPa. To examine the effect of thixotropy corresponding to wide range of water content, the correlations of normalized $G/G_{24}$ and $w/L_L$ are plotted in Fig. 5(b). Fitting curves are drawn by excluding the three encircled data. It can be recognized in the figure that thixotropic effect on $G$ is prominent at around $L_L$, and at lower and higher water contents the thixotropic hardening becomes less remarkable.

As pointed out by Mitchell (1960), the water content has been used as a primary parameter to evaluate the magnitude of soil strength gained by thixotropy, which is resulted from the alteration of internal soil structure between dispersion and flocculation. The range of water content between plastic limit ($w_p$) and liquid limit ($w_{L_L}$) affecting the thixotropy has been discussed by many researchers, for example Skempton and Northey (1952) and Seed and Chan (1957). They suggested that thixotropic effect at or close to $w_p$ can be very low or cannot be observed. Most past investigations presented that increasing water content caused increase in thixotropic effect.

However, Skempton and Northey showed the consistent increases of thixotropic effects only from $w_p$ until $L_L$, then over $L_L$ value some samples remained increasing, but some dropped off. Mitchell (1960) conducted the experiment on compacted clay in the range of $w$ from 0.36 to 0.90 of $L_L$ and found that thixotropy had the greatest effect at $w$ between about 0.56 to 0.74 of $L_L$. Therefore, the information of $w$ effect at the range over $L_L$ is still unclear in the previous literatures.
Between the ranges of $w/w_L$ from 0.75 to 1.35 in this experiment, effect of thixotropy is found increasing from 0.75 to 1.0 of $w/w_L$ ratio, which is consistent with Skempton and Northe (1952), but over $w_L$ the thixotropic effect is decreasing. Nonetheless, the upper boundary of water content without thixotropic existence is not yet drawn even at 1.35 time of $w_L$. Suthaker and Scott (1997) carried out tests on thixotropic strength of oil sand fine tailings which contained extremely high $w$ more than 8 times of $w_L$ and proved that thixotropic effect still existed; nonetheless, its properties differ from marine clays. In the case of Tokuyama dredged clay, natural water content contains only 1.20 times of $w_L$, at which point thixotropic effect still pronounced. From this finding, it implies that thixotropy may play an important role in altering the properties of natural soil.

**Figure 3.** Measurement of thixotropic hardening by bender element test for Kasaoka clay with 60.6% of water content

**Figure 4.** Measurement of thixotropic hardening $G$ by bender element tests

**Figure 5.** (a) Relationship between $G$ and $w/w_L$; (b) Normalized $G/G_{24}$ versus $w/w_L$

### Undrained Shear Strength by Laboratory Vane Tests

**Cement-Treated Soils**

To investigate the strength development of CTS, vane shear tests were conducted during the hardening process to a curing time of 300 min. The test results are summarized in Fig. 6 for both Fujinomori and Kasaoka clays. Similar to the $G$ values measured in the bender element tests, the strength increases with the curing time. The rate of increase is dependent on the mixing conditions. Obviously, at the same water content, samples with more cementing agent show higher levels of strength. However some specimen, $s$, values were almost constant with curing time, for example, in the case of $w/C=60:4$ and $w/C=70:4:7$ for Fujinomori clay. This is due to the difference in the accuracy of the measurements between the vane shear and the bender element tests, or to the fact that the shear strength has not developed in the same manner as $G$. This point will be discussed in further detail in the next section.

**Very Soft Clays**

The stiffness of very soft clays is found to increase owing to thixotropic phenomenon as mentioned in the above section. The increase in the strength caused by
Also soil properties, on test and on coefficient of about 1000. In addition, they behave the similar way when
mainly focusing on strength and stiffness during the study, together with the results of tests conducted by Terashi et al. (1983). In the relation indicated by the "high range correlation", the strength, including that by Terashi et al. (1983), was measured by unconfined compression tests. Terashi et al. (1983) also carried out unconsolidated undrained (UU) triaxial tests on CTS samples under various levels of confining pressure and confirmed the validity of the shear strength as \( s_u = q_u / 2 \).
As has already been mentioned, the \( G \) value in this study was obtained by bender element testing, while Terashi et al. measured \( G \) by resonant column testing. It should be noted that since unconfined compression tests require a certain level of strength, so that the sample will be strong enough to stand on its own, the lowest \( s_u \) value obtained from these tests was about 10 kPa. It is of interest that a linear relation between \( G \) and \( s_u \) also exists over 4 orders of magnitude for \( G \) and \( s_u \), i.e., \( s_u \) ranges between approximately 0.2 kPa and 2000 kPa. It is found that the relation can be fitted quite well by a power function with a regression coefficient of about 94%, as expressed in Eq. (4), namely,

\[
G = 310 s_u^{1.06}
\]  

(4)

It should be noted that the power of \( s_u \) is very close to 1.0, indicating that \( G \) is about 300 times greater than \( s_u \), regardless of the strength magnitude or \( G \). It is well known that employing seismic waves, such as in a surface wave exploration, can be a very effective way of confirming the quality after the filling of the CTS. Using the above relation, the strength can easily be estimated from a seismic survey.

As for very soft clays, the relationship between thixotropic hardening \( G \) and \( s_u \) at various elapsed times is shown in Fig. 9 together with that obtained from CTS material. Generally, a linear trend can be identified. However it is observed that at very high water content corresponding to low initial strength, \( s_u \) remains constant until a certain time unlike \( G \). After \( G \) reaches a certain values, \( s_u \) starts to increase.

The correlations between \( G \) and \( s_u \) of CTS and very soft clays are almost in the same trend as shown in Fig. 9. In addition, they behave the similar way when the strengths are extremely small, i.e., \( G \) increases prior to \( s_u \). Both behaviors, the constant values and slow increases of \( s_u \), are quite interesting and might be associated with viscosity or strain rate effect which is obviously an important factor governing soil strengths especially when material remains soft; however further investigation is necessitated to confirm this presumption. Alternative explanation for constant \( s_u \) until certain times may be attributed to the order of strain level, as presented by Seed and Chan (1957), and Mitchell (1960). They investigated thixotropic strength of compacted clays using triaxial compression test and reported that the strength ratio measured at smaller
strains appears much greater than at large strains. The strain level measured by the bender element test, which was adopted in this study, is less than 0.001%, while the strength obtained by vane test corresponds to large strain, where the progressive failure to attain the peak strength may destroy weak bounds created by cement or thixotropy hardening process. Another reason for the constant $s_u$ may be attributed to disturbances during the insertion of the vane blade. When a specimen is too soft, the insertion of vane blade might destroy the particles bounding created by cement or thixotropy.

Furthermore, to check the applicability of the test results with other materials, the relation between $G$ and $s_u$ was plotted with correlations of natural clays investigated by in situ testing from various parts of the world, as shown in Fig. 10. The $G$ values for all the natural clays were determined using Seismic Cone Penetration Tests (SCPT). The strength were mostly obtained using Field Vane Tests, except for those of Yamashita and Bangkok clays, which were measured by Unconsolidated Undrained and Unconfined Compression tests, respectively. Tests were carried out by the authors’ geotechnical group, except for those performed by Bothkennar and Louiseville, whose data are referenced in Hamouche et al. (1995) for Louiseville and Nash et al. (1992) for Bothkennar. Details on the properties of other natural clays may be found in Tanaka et al. (2001a, 2001b). As can be seen from the figures, it is interesting to note that the strength and stiffness correlation of natural clays is concentrated around the relationship based on Eq. 4. It is implied that the mechanism of the CTS behavior is remarkably similar to that of natural clays and very soft clays from this experiments.

![Figure 9. Correlation between $G$ and $s_u$ for very soft clays](image)

![Figure 10. Correlation between $G$ and $s_u$ for natural clays](image)

**Conclusions**

The experimental studies on properties of very soft clays with and without cement treatment have been carried out and the main conclusions can be drawn as following:

1) Bender element test is a powerful tool and an appropriate method for evaluating the hardening stiffness of geomaterials, since it is able to detect even small changes in $G$ with an extremely small strain.

2) Regardless of soil types, thixotropy affects the clay most strongly at around liquid limit state and becomes less remarkable at lower and higher water contents.

3) A relationship between the shear modulus and the shear strength for a wide range of values is proposed as approximately $G = 300 \times s_u$, where $s_u$ is the undrained shear strength. This relation serves as a useful tool for monitoring the quality of materials in practice, since the shear wave velocity can easily be investigated in the field.