ABSTRACT: A Liquefied Stabilized Soil (LSS) is one of a cement-stabilized soil, which is improved the soil properties by the effect of cementation arising in an excavated soil mixed with cement and water. LSS has been used extensively as a back filling soil for cut and covered tunnels or invert part of shield tunnels from the viewpoint of recycling the excavated soil from underground construction sites on urban area in Japan. In this paper, the strength and deformation properties of Liquefied Stabilized Soil mixed with fibered material were evaluated by a series of unconfined compression tests. It was found that the deformation property of LSS mixed with the fibered material becomes ductile and the strength increases by 10% compared to the strength of LSS of no fibered material.

1 INTRODUCTION

In these years, the amount of generating of industrial waste is increasing with development of economic growth. Especially, the rate of the excavated soil in industrial waste is large, and this recycling is desired. Many efficient uses are attempted to various industrial wastes. Many studies are performed for a strength and deformation characteristics of cement-treated soil mixed with a polyester fiber or a plastic waste material (e.g. Yokota et. al. 2002) as reinforced material of geomaterials in the field of geotechnical engineering. Recently, Liquefied Stabilized Soil (LSS) has been used extensively as a back filling soil for cut and covered tunnels or invert part of shield tunnels from the viewpoint of recycling the excavated soil from underground construction sites on urban areas in Japan. LSS is one of a cement-stabilized soil, which is improved the soil properties by the effect of cementation arising in an excavated soil mixed with cement and water. These stabilized soils flow like concrete mortar before hardening, require no compaction at the time of placing, and induce little volumetric changes in hardening (Koda et. al. 2000, Kuno et. al. 2003). However, it is considered that the aseismatic performance of LSS decreases with increasing the strength of LSS, and the deformation property shows brittle behavior similar to a cement-treated soil. It is possible that the application of LSS at re-excauation site becomes difficult since the strength increases with increasing cement content. Therefore, it is an important subject to improve a brittle mechanical property and to try to increase a ductile performance.

In this study, a fibered material was mixed to LSS in order to increase a ductile performance of LSS. The strength and deformation properties of LSS mixed with fibered material are evaluated by a series of unconfined compression tests with local axial strain measurements. Based on test results, this paper investigates the effects of shape and quality of fibered material, fibered material content and curing time on the mechanical properties of LSS mixed with fibered material.

Table 1 Physical properties of NSF- Clay

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of particle $\rho_s$ (g/cm$^3$)</td>
<td>2.762</td>
</tr>
<tr>
<td>Liquid Limit $w_L$ (%)</td>
<td>60.15</td>
</tr>
<tr>
<td>Plastic Limit $w_p$ (%)</td>
<td>35.60</td>
</tr>
<tr>
<td>Plasticity Index $I_p$</td>
<td>24.46</td>
</tr>
</tbody>
</table>
2 TEST PROCEDURE

2.1 Test materials

In this study, the NSF-Clay on the market was used in consideration of the homogeneity of material. This clay was assumed as an excavated soil. The physical properties of NSF-Clay are shown in Table 1. The general cement stabilizer (Geoset 10 by Taiheiyo Cement Co. Ltd.) as the hardening agent was used. This cement is used extensively for an improvement of soft ground in Japan. A newspaper and a regular paper on the market (70 g/m²) were used as fibered materials. A crushed newspaper was made as follows: A newspaper was cut out to a suitable size with the office shredder. A cut newspaper was crushed with water by using food processor for coking. After dried it in a drying oven, untied it by the hand, it was crushed again to smaller pieces like cotton with food processor. A strip of newspaper and regular paper was made cutting those into 2 cm in width and 10 cm in length.

The slurry of LSS was designed based on the results of a comprehensive series of laboratory test and comprised of cement 200 kg for 1 m³ of slurry material, water and NSF-Clay so that the density of slurry might become 1.250 g/m³. The amount of cement and density of slurry were found to satisfy the following requirements. The unconfined compressive strength qₜ should be larger than 180 kN/m² for stability of the back filling, while strength at a curing time of 28 days less than 500 kN/m² was preferred for smooth re-excavation. The flow value should be larger than 250 mm for pumping slurry material.

Figure 1 shows the relation among the qₜ, the flow value, and the density of slurry ρₛ. It is found that the density of slurry to satisfy above requirements is the range from 1.248 g/m³ to 1.253 g/m³. The proportion of paper content was set to 0 (no fibered material), 5, 10, 15 and 20 kg for 1 m³ of slurry. After the slurry of LSS had been made, the flow test was performed to examine the flow property of slurry.

Figure 2 shows the relation between the flow value and the paper content for each mixed paper type. The flow value of crushed newspaper decreases with increasing the paper content, whereas the flow values of strip types are not decrease. The reduction of flow value seems to be depended the shape of fibered materials.

A fibered material was added to the slurry adjusted to a prescribed density. Afterwards, the vacuum pressure of 98kPa was applied to the sample for ten minutes, and the bubble of the sample was removed. The sample was filled to a mold of 5 cm in diameter and 10 cm in height, and the top face was covered with the polymer film. The LSS sample filled in a mold was cured to 7, 14, 21, 28 and 189 days in wet air under 20 ± 3 °C.

Table 2 shows the paper content, the density of slurry ρₛ, the density of LSS before mixing fibered material ρₗS and the wet density of specimen ρₜ at a curing time of 28 days for each sample. The ρₛ have been installed
within the range of \( \pm 0.001 \) g/cm\(^3\) for the prescribed value 1.250 g/cm\(^3\).

### 2.2 Testing methods

A series of the unconfined compression tests were performed at the axial strain rate of 1 \%/min at the prescribed curing time. The specimen dimensions are 5 cm in diameter and 10 cm in height.

Figure 3 shows a schematic view of the unconfined compression test apparatus. Axial loads were measured by a load cell installed on the top cap. Axial strains were measured locally by means of a pair of Local Deformation Transducers (LDTs, Goto et al., 1991) attached at the diagonally opposite ends of the diameter of the cylindrical specimen. An external displacement transducer and a proximity transducer were also used to monitor, respectively, the displacement of the loading piston and the top cap of the specimen. Large effects of bedding error are included in externally measured axial strains.

### 3 TEST RESULTS AND DISCUSSION

#### 3.1 Effect of shape and quality of fibered material

Figures 4 shows the relationships between deviator stress \( q \) and axial strain \( \epsilon_a \) for unconfined compression test at a curing time of 28 days. Fig. 4 (a) shows the results for paper content of 5 kg/m\(^3\), Fig. 4 (b) shows it for 10 kg/cm\(^3\) and Fig. 4 (c) shows it for 20 kg/m\(^3\), respectively. The value of unconfined compressive strength \( q_u \) for the specimen mixed with fibered materials is about 10 \% larger than the value of \( q_u \) in no fibered material. The decrease rate of \( q - \epsilon_a \) curve after the peak becomes small with increasing paper content. It is found that the ductile performance is improved by adding a fibered material. However, the decrease rate of \( q - \epsilon_a \) curve after the peak in the strip of newspaper and regular paper is larger than that in crushed newspaper. The improvement effect of the ductile performance in a crushed newspaper is larger than that in a strip of newspaper and regular paper.
Figure 5 shows a comparison of $q - \varepsilon_a$ curve for each paper contents in crushed newspaper at a curing time of 28 days. The $q - \varepsilon_a$ relations of paper content of 10 kg/m$^3$ or more is almost the same. The value of $q$ hardly decreases to about $\varepsilon_a = 6\%$ after the peak. Especially, the value of $q$ at $\varepsilon_a = 14\%$ remains about 50% compared with the value of $q_u$ in the paper content of 20kg/m$^3$. It is found that the improvement effect of the ductile performance on LSS is different by the kind of fibered materials.

Figure 5 Comparison of $q$ vs $\varepsilon_a$ relations for paper content
3.2 Effect of curing time

3.2.1 Stress-strain relationships

Figures 6 - 10 show the q - ε₀ relations of unconfined compression test for each mixture condition at a prescribed curing time. Figs (a) show the q - ε₀ relations up to ε₀ = 15 %, Figs (b) show that at the small strain level up to 0.01 %. The q₀ increases with an increase in the curing time. The q - ε₀ relations after the peak at a curing time of 189 days shows the decreasing tendency with all cases. It is considered that the reinforcement effect due to add a paper became relatively small, since the q₀ of LSS increased by a long curing period. On the other hand, it is found that the initial stiffness increases so that the cementation may increase by a long curing period from the q - ε₀ relations at the small strain level (Fig 6(b) - 10(b)). This tendency is similar to that shown the cement-treated sandy soil (Kohata et. al., 1997., Tatsuoka et. al., 1997).

In order to estimate the ductile performance after the peak, the degree of ductility after the peak was defined in this study. The degree of ductility is a value in which the axial strain εᵣ at q₀/2 after the peak is divided by the axial strain εᶠ at the peak, i.e. the value is εᵣ / εᶠ.

The relationship between the degree of ductility εᵣ / εᶠ and curing time of 28 and 189 days is shown in Figure 11. The scattering of the results is large since the cementation develops rapidly before a curing time of 28 days. Therefore, the results before a curing time of 28 days was excluded since it was considered that the ductile property could not be estimated. The εᵣ / εᶠ for no fibered material and a strip of regular paper shows almost same values at a curing time of 28 days. It is considered that the effect of improvement cannot be so expected in a strip of regular paper. On the other hand, the εᵣ / εᶠ for a crushed newspaper is about twice compared with other cases, and the remarkable effect of the improvement was achieved in a crushed newspaper. The εᵣ / εᶠ at a curing time of 189 days show a decreasing tendency or constant value except for a crushed newspaper of 20 kg/m³. The εᵣ / εᶠ of a crushed newspaper of 20 kg/m³ increases remarkably, whereas the εᵣ / εᶠ of a crushed newspaper of 10 kg/m³ decreases greatly. However, when comparing it with the εᵣ / εᶠ of no fibered material at a curing time of 189 days, the εᵣ / εᶠ of a strip of regular paper of 10 and 20 kg/m³ are similar and 1.5 times, and that of a crushed newspaper of 10 and 20 kg/m³ are twice and 3 times, respectively.
Therefore, it is considered that it is the most effective to add a crushed newspaper to LSS in order to improve the ductile performance in a long curing period.

3.2.2 Tangent Young’s modulus

Figures 12 show the relationship between q and normalized tangent Young’s modulus $E_{\text{tan}}/E_{\text{max}}$. The maximum Young’s modulus $E_{\text{max}}$ was obtained from the initial linear elastic part of stress-strain curve at axial strains $\varepsilon_a$ less than about 0.001% measured with LDTs. The tangent Young’s modulus $E_{\text{tan}}$ was obtained from each stress-strain curve. The $E_{\text{tan}}/E_{\text{max}}$ at the initial portion of loading shows the tendency not to decrease with an increase in the curing time, whereas the $E_{\text{tan}}/E_{\text{max}}$ decreases suddenly from the initial portion of loading with a decrease in curing time. This tendency is remarkable when adding a fibered material. The deformation property in small strain level at the initial portion of loading becomes more linear. This property is similar to that of cement-treated sandy soil.

3.2.3 $q_u$ and $E_{\text{max}}$

Figure 13 shows the relationship between $q_u$ and curing time $t_c$ by both logarithms. It is found that the log ($q_u$) - log ($t_c$) relation is linear. A similar relation is reported in the research on the cement-treated sand (Sugo...
et. al., 1998). The gradient 'n' by a linear fit in both loga-

The gradient of the

The gradient of the
case to add a fibered material

That is, it is

increase of strength with a curing time

considered that an increase

becomes small when adding

fibered material. It seems

that $q_u = a (t_c)^b$ is approved to

to the relation between $q_u$ and $t_c$

cement-treated soil including

Figure 14 shows the

relationship between $E_{\text{max}}$

and $t_c$. The $E_{\text{max}}$ of the case to

add a fibered material is

obviously large compared with

$E_{\text{max}}$ of the case of no fibered

material at a curing time of

189 days, whereas $E_{\text{max}}$

obtained before a curing time of

28 days has scattered. This

tendency is remarkable in a

crushed newspaper compared

with a strip of newspaper. It

is found that the kind of a fi-

bered material and the

amount of content of a fi-

bered material influence an

increase of $E_{\text{max}}$ by a long

curing period.

3.3 $E_{\text{max}}, E_{50}$ and $q_u$ rela-

tions

Figure 15 shows the comparison of $E_{\text{max}} - q_u$ relation and $E_{50} - q_u$ relation. $E_{50}$ was obtained from the secant
gradient between the coordinate origin and the point of $q_u/2$ on the stress - strain curve. There is a relation be-

tween $E_{\text{max}} \approx 1000 - 3000 \cdot q_u$ and $E_{50} \approx 500 - 1000 \cdot q_u$ regardless of a curing time or shape and quality of a fi-
bered material. The $E_{\text{max}}$, $E_{50}$ and $q_u$ relations are similar to that of cement-treated soil obtained from the LDT measurements.

### 3.4 Failure situation of specimen

Figure 16 (a) - (c) show the comparison of failure situation for no fibered material, crushed newspaper of 20 kg/m$^3$ and a strip of regular paper of 20 kg/m$^3$, respectively. In the case of no fibered material (Fig. 16 (a)), the crack was caused in a vertical direction and it has collapsed. In the case adding crushed newspaper of 20 kg/m$^3$ (Fig. 16 (b)), a finer wrinkle crack is caused on the surface of specimen, and it has collapsed. In the case to add a strip of regular paper of 20 kg/m$^3$ (Fig. 16 (c)), a fine crack is not seen on the surface of specimen, and the failure surface is caused clearly for diagonal direction. This clear failure surface was seen also in the case to add a sprit of newspaper of 10 kg/m$^3$. It seems that the failure pattern depends on the kind of fibered material. It is considered that a shape of fibered material influences the effect of reinforcement from the result that the improvement effect of ductile performance for the case to add a crushed paper is large compared with that for the case to add a strip paper. That is, it is considered that the finer fibered material acts as an effect to inhibit progress of failure surface.

### 4 CONCLUSIONS

The following conclusions were derived from the results of unconfined compression tests on LSS and LSS mixed with fibered materials.

1. The reduction of flow value depends on the shape of the fibered material.
2. The unconfined compressive strength increases about 10% due to add a fibered material.
3. The improvement effect of ductile performance in a crushed newspaper is larger than that in a strip of newspaper and regular paper. It is the most effective to add a crushed newspaper to LSS in order to improve the ductile performance in a long curing period.
4. It seems that $q_u = a (t_c)^b$ is approved to the relation between $q_u$ and $t_c$ of cement-treated soil including LSS.
5. It is considered that the finer fibered material acts as an effect to inhibit progress of failure surface.
6. The deformation properties on the unconfined compression test depends on the cementation of mixture cement before a peak and depends on the effect of reinforcement of fibered material after a peak.

### REFERENCES


