Effects of solidification strength on the shear properties of materials mixed wood chips with converter steelmaking slag

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ABSTRACT

In this study, triaxial compression tests were performed on wood chips mixed with steelmaking slag and blast furnace slag fine powder (BFSFP). To understand the manner in which the mechanical properties changed with the difference in the shape of the wood chips and the amount of BFSFP in the mixture, two types of wood chips (fibrous cocopeat and granular hinoki) were used. Consequently, it was found that the difference in the shape of the wood chips had different effects on the mechanical properties of the mixed material when the mixing ratio of BFSFP was low. Moreover, it was found that the shear strength of the slag containing a few percentage of wood chips was higher than that of the slag without wood chips.

Keywords: wood chips, steelmaking slag, blast furnace slag fine powder, geo-material, solidification properties

1 INTRODUCTION

Japan’s land area comprises only 0.28% of the world’s land mass. However, 20.5% of all earthquakes worldwide of magnitude 6 and above have occurred in Japan. This makes Japan one of the most earthquake-prone countries in the world. The Tohoku-Pacific Ocean Earthquake generated a huge amount of disaster waste of roughly 30 million tons, including tsunami deposits, and the Kumamoto Earthquake resulted in roughly 3 million tons. The majority of these disaster wastes is composed of the under-sieve residue, which contains a large amount of wood chips. The under-sieve residue was not reused due to lack of support and because the effects and processes occurring during the decay of the wood chips were unknown. Under-sieve residue is a sediment fraction obtained using a vibrating and rotating sieve machine set to a sieve size of less than 20 mm. This results in large variations in the shapes and sizes of the wood chips, and the result also vary depending on the disposal site this residue was obtained from (Takai et al. 2016). Proposals for an effective use of under-sieve residue would not only reduce the amount of residue that ends up in the final disposal sites by promoting utilization but also enable rapid reconstruction and restoration after a disaster by using already existing materials.

Large quantities, approximately 14 million tons annually, of steelmaking slag are generated as an industrial by-product during the production of crude steel. Steelmaking slag is characterized by its good hydraulic properties (Karamacharya et al. 1979), excellent wear resistance, and a larger internal friction angle than ordinary soil (Horii et al. 2012). Currently, it is widely used as a roadbed material, etc. However, with the recent reduction in public works expenditure, the expansion of the market has become an issue.

In this paper, the authors believed that the under-sieve residue could be effectively used as a geo-material by solidifying it with steelmaking slag.

Our previous studies have shown that the strength of steelmaking slag increases over time (Yoshikawa et al. 2018a). In contrast, it has been found that some steelmaking slags do not show a solidification reaction even when compacted (Yoshikawa et al. 2018b). To promote and assist the hydraulic solidification reaction of steelmaking slag, it is necessary to add subsidiary material. Before conducting these experiments, the authors conducted unconfined compression tests using blast furnace slag fine powder (BFSFP), ordinary Portland cement, and hemihydrate gypsum to select an appropriate subsidiary material. The results show that, when BFSFP was added, the axial stress after 7 days of curing was larger than that of ordinary Portland cement,
and the rate of increase of the strength between 7 and 28 days of curing was also significant. In addition, hemihydrate gypsum is difficult to handle and has poor workability (Yoshikawa et al. 2018c).

Based on the abovementioned results, in this study, BFSFP was used as a subsidiary material. The triaxial consolidated drained compression tests (hereinafter referred to as CD tests) were conducted to understand the effects differing amounts of BFSFP, different mixing ratios and type of wood chips, and the curing period would have on the mechanical properties of the mixed material of slag (hereinafter, a mixture of steelmaking slag and BFSFP is referred to as slag).

2 EXPERIMENT

2.1 Materials and test methods

In this study, four types of materials were used: steelmaking slag without aging treatment (\(\rho_s=3.35\) g/cm\(^3\), \(D_{50}=0.75\) mm, hereinafter referred to as steelmaking slag), BFSFP4000 (\(\rho_s=2.89\) g/cm\(^3\)), fibrous coconut berry (\(\rho_s=0.53\) g/cm\(^3\), 100 samples: average diameter: 0.27 mm, average length: 24.4 mm, hereinafter referred to as cocopeat), granular hinoki (\(\rho_s=0.41\) g/cm\(^3\), 100 samples: average length: 0.7 mm*1.4 mm*3.3 mm). Ion exchange water was used as pore water.

Figure 1 shows the grain size distribution curve of the steelmaking slag used for this test. The target compaction density and the water content ratio of the mixed material, comprising wood chips and slag4 (hereinafter referred to as the mixture of steelmaking slag and BFSFP with a mass ratio of 96: 4) were determined by compaction tests of the mixed material. Figure 2 shows images of each sample. Figure 3 shows the results of the compaction tests of the mixed materials of wood chips and slag4, which were performed according to the A-b method (JIS A 1210). Only one or two samples were tested under each condition owing to the limited amount of available samples. In addition, the results of previous studies (Yoshikawa et al. 2017) have shown that the dry density of a mixed material comprising steelmaking slag and wood chips of this particle size range changes scarcely, even when the water content is changed. Compaction tests were conducted to estimate the water content just before the occurrence of over-compaction. As shown in Figure 3, the maximum dry density and the optimum water content varied with the mixing ratio of the wood chips. The target dry density of the specimen was reached at a compaction degree \(D_c\) of 95%.

The specimen was mixed with naturally dried wood chips and steelmaking slag, subsequently ion-exchanged water was added, and finally BFSFP was mixed into it. The amount of ion-exchanged water was adjusted so that the water content ratio was just at the point before over-compaction would take place, when all the materials were mixed. The compaction tests were not performed with mixtures containing slag15 (hereinafter referred to as the mixture of steelmaking slag and BFSFP with a mass ratio of 85: 5). Therefore, the target dry density and the target water content ratio under each experimental condition were determined based on the test results shown in Figure 3. The target water content ratio was increased by 3% from the water content ratio of slag4. The sample was placed in a hollow cylindrical mold with a diameter of 50 mm and a height of 100 mm for the preparation of the test specimens. Each specimen was sealed and cured at a constant temperature of 20 °C for 7 or 28 days. Table 1 lists the specimen preparation conditions that were used to prepare the test samples. The CD tests were conducted on the specimens once they reached their prescribed curing duration. In the CD tests, each specimen was saturated with a back pressure of 200 kPa, isotropically consolidated at an effective confining pressure of 50 kPa, and compressed under drained conditions with an axial strain rate of 0.01%/min. The CD tests were conducted up to an axial strain of \(\varepsilon_{50}=22\%\) at which point the wood chips were included into the material.

![Fig. 1. Grain size distribution curve of the steelmaking slag.](image1)

![a. Steelmaking slag  b. BFSFP](image2)

![c. Cocopeat  d. Hinoki](image3)

![Fig. 2. Sample images (Steelmaking slag, BFSFP, Cocopeat, Hinoki).](image4)
Fig. 3. Compaction curves of slag with different wood chips mixing ratios.

Table 1. Specimen preparation conditions.

<table>
<thead>
<tr>
<th>Wood chips types</th>
<th>Mixing ratio (vol%)</th>
<th>Target dry density $\rho_t$ (g/cm$^3$)</th>
<th>Water content ratio w (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- (Slag4)</td>
<td>0</td>
<td>1.92</td>
<td>12.0</td>
</tr>
<tr>
<td>Cocopeat</td>
<td>5</td>
<td>1.82</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.68</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>1.07</td>
<td>25.0</td>
</tr>
<tr>
<td>Hinoki</td>
<td>10</td>
<td>1.83</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>1.49</td>
<td>25.0</td>
</tr>
</tbody>
</table>

b. Series 2: Slag15

<table>
<thead>
<tr>
<th>Wood chips types</th>
<th>Mixing ratio (vol%)</th>
<th>Target dry density $\rho_t$ (g/cm$^3$)</th>
<th>Water content ratio w (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- (Slag15)</td>
<td>0</td>
<td>1.92</td>
<td>15.0</td>
</tr>
<tr>
<td>Cocopeat</td>
<td>5</td>
<td>1.82</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.68</td>
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<tr>
<td></td>
<td>33</td>
<td>1.49</td>
<td>28.0</td>
</tr>
</tbody>
</table>

2.2 Experimental results of the blast furnace slag fine powder 4 wt% mixed material (SERIES 1)

Figure 4 shows the relationship between the deviator stress $q$ and the axial strain $\varepsilon_a$ as obtained from the CD tests of slag4 mixed with cocopeat in the mixing ratios of 0%, 5%, 10% and 33% by volume at 7 or 28 days of curing. The circles on each plot indicate the value of the shear strength $q_{max}$ for each sample. At a cocopeat mixing ratio of 33 vol%, the deviator stress continued to increase until the end of the CD test. Therefore, the deviator stress at the end of the CD test was regarded as $q_{max}$ and plotted as such. As shown in Figure 4, the peak appeared at an axial strain of less than 5%, and then softened regardless of the curing periods for a cocopeat mixing ratio of less than 10 vol%. On the contrary, at a cocopeat mixing ratio of 33 vol%, no peak appeared until an axial strain of $\varepsilon_a=22\%$. Furthermore, focusing on the stress reduction rate after the peak strength, it gradually decreased with an increase in the mixing ratio of the cocopeat. In addition, the residual strength was almost the same regardless of the cocopeat mixing ratio. $q_{max}$ and the stiffness of the cocopeat mixing ratio of less than 10 vol% increased by curing. In the case of the cocopeat mixing ratio of 33 vol%, there was no remarkable change in $q_{max}$ and the stiffness with a longer curing duration.

Figure 5 shows images of the specimens after the CD tests were performed. As visible in Figure 5, a clear shear band on the surface of the specimen was observed at a cocopeat mixing ratio of less than 10 vol%. In contrast, at a cocopeat mixing ratio of 33 vol%, the clear shear band on the surface of the specimen was not observed, and the specimen was deformed into a barrel shape. The conclusion that the properties of the cocopeat are greatly affected by the mechanical properties of the mixed material was drawn from the results of the cocopeat specimen with a mixing ratio of 33 vol%.

Figure 6 shows the relationship between the deviator stress $q$ and the axial strain $\varepsilon_a$ as obtained from the CD tests of slag4 mixed with hinoki in a mixing ratio of 0%, 10% and 33% by volume at 7 or 28 days of curing. The peak appeared at an axial strain of less than 5%, and then softened, regardless of the curing period and under all conditions. Additionally, $q_{max}$ and the stiffness at the hinoki mixing ratio of 33 vol% was smaller than those of slag4. The stress-strain curve of the hinoki mixing ratio of 33 vol%, is quite different from that of the cocopeat mixing ratio of 33 vol%, as shown in Figure 4. The difference in the shape of the wood chips greatly affected this result. In addition, as shown in Figures 4 and 6, although the stress-strain curves of the cocopeat and hinoki mixing ratio of 10 vol% varied with the curing period, no difference was observed in $q_{max}$ regardless of the curing period. Additionally, the decrease in stress after $q_{max}$ was more gradual for the mixture with the fibrous cocopeat. In other words, when the wood chips mixing ratio was approximately 10 vol%, the effects of the differences in the shape of the wood chips on $q_{max}$ was small, however, the effect on the decrease of the deviator stress after $q_{max}$ was reached was considered to be large. Additionally, it was found that the material with highest toughness is obtained when fibrous cocopeat was added.

Figure 7 shows the change in the shear strength due to the difference in the mixing ratio of wood chips. At a cocopeat mixing ratio of 33 vol%, the maximum deviator stress was not reached until the end of the CD test. Therefore, it was not possible to compare the case of the cocopeat mixing ratio of 33 vol% with the hinoki mixing ratio of 33 vol%. When the mixing ratio of wood chips was less than 10%, $q_{max}$ was larger with wood chips than with slag4, regardless of the shape of the wood chips and the curing period.

Figure 8 shows the relationship between the axial strain $\varepsilon_a$ and the wood chip mixing ratio, when the deviator stress $q$ is half of the shear strength $q_{max}$. The red circles plotted in Figure 8 show $q_{max}$ at a cocopeat mixing ratio of 33 vol%. As mentioned above, when the
cocopeat mixing ratio was 33 vol%, the maximum deviator stress was not reached until the end of the CD test. Therefore, this result was calculated assuming the deviator stress $q$ at the end of the CD test to be equal to $q_{\text{max}}$. From Figure 8, it can be seen that $\varepsilon_{50}$ increased rapidly with an increase in the cocopeat mixing ratio. On the contrary, $\varepsilon_{50}$ did not increase much when hinoki was mixed in. Thus, the relationship between $\varepsilon_{50}$ and the wood chips mixing ratio was quite different and clearly dependent on the shape of the wood chips used. The rate of increase of $\varepsilon_{50}$ was larger with an increasing mixing ratio, when fibrous cocopeat was mixed in than when granular hinoki was mixed in.

![Fig. 4. $q$-$\varepsilon_a$ curves of slag4 mixed with cocopeat.](image)

![Fig. 5. Image of each specimen after CD tests (Slag4, Cocopeat 5 vol%, Cocopeat 10 vol%, Cocopeat 33 vol%, from left to right).](image)

![Fig. 6. $q$-$\varepsilon_a$ curves of slag4 mixed with hinoki.](image)

2.3 Experimental results of the blast furnace slag fine powder 15 wt% mixed materials (SERIES 2)

Figure 9 shows the relationship between the deviator stress $q$ and the axial strain $\varepsilon_a$ as obtained from the CD tests of slag4 mixed with cocopeat in the mixing ratios of 0%, 5%, 10% and 33% by volume at 7 or 28 days of curing. The circles on each plot indicate the value of the shear strength $q_{\text{max}}$, for each sample. From Figure 9 it can be seen, that $q_{\text{max}}$ increased under each mixing condition as the curing period increased, with the exception of the cocopeat mixing ratio of 33 vol%. In addition, $q_{\text{max}}$ tended to decrease as the cocopeat mixing ratio increased. In particular, at a cocopeat mixing ratio of 33 vol%, not only was the deformation modulus extremely small, but the deviator stress continued to increase even at the end of the CD test. In Figure 4, $q_{\text{max}}$ of slag4 mixed with cocopeat tended to be slightly larger than that of only slag4. However, under the conditions of the $q_{\text{max}}$ of the slag exceeding 3000 kPa, $q_{\text{max}}$ decreased due to the mixing in of cocopeat.

![Fig. 7. Relationship between $q_{\text{max}}$ and wood chips mixing ratio.](image)

![Fig. 8. Relationship between $\varepsilon_{50}$ and wood chips mixing ratio.](image)

Figure 10 shows the relationship between the deviator stress $q$ and the axial strain $\varepsilon_a$ as obtained from the CD tests of slag4 mixed with cocopeat in the mixing ratios of 0%, 10% and 33% by volume at 7 or 28 days of curing. As in Figure 9, $q_{\text{max}}$ decreased with the mixing in of cocopeat. In the stress-strain curve for cocopeat at a mixing ratio of 33 vol%, $q_{\text{max}}$ was observed to be near $\varepsilon_a=2.5\%$, unlike the case of mixing cocopeat. Also, when the hinoki mixing ratio was increased to 33 vol%, both $q_{\text{max}}$ and the stiffness decreased significantly.
3 COMPARISON OF SLAG4(SIRIES1) AND SLAG15(SIRIES2) TEST RESULTS

Figure 11 shows the relationship between the normalized shear strength $q_{\text{max}}/q_{\text{max,Slag}}$ and the cocopeat mixing ratio. $q_{\text{max}}/q_{\text{max,Slag}}$ is the value obtained by dividing the $q_{\text{max}}$ of the cocopeat mixed material by the $q_{\text{max,Slag}}$ of the slag of the same amount of BFSFP and the same curing period. For example, $q_{\text{max}}$ of slag4 mixed with cocopeat at 7 days of curing was divided by $q_{\text{max}}/q_{\text{max,Slag}}$ of slag4 at 7 days of curing. Additionally, $q_{\text{max}}$ of slag15 mixed with cocopeat at 28 days of curing was divided by $q_{\text{max}}/q_{\text{max,Slag}}$ of slag15 at 28 days of curing. As can be seen in Figure 11, when cocopeat was mixed with Slag15, the maximum deviator stress decreased with an increase in the cocopeat mixing ratio regardless of the curing period. In contrast, when cocopeat was mixed with Slag4, $q_{\text{max}}$ was not reduced by the mixing in of cocopeat, regardless of the curing period. In other words, the effect of cocopeat on the stress-strain curve of the mixed material differed depending on the amount of subsidiary material present.

Figure 12 shows the relationship between the normalized shear strength $q_{\text{max}}/q_{\text{max,Slag}}$ and the hinoki mixing ratio. From Figure 12, as in the case of mixing in cocopeat, it was found that when hinoki was mixed with slag15, the rate of decrease in the deviator stress with increasing wood chips mixing ratio was larger than when hinoki was mixed with slag4. From Figures 11 and 12, it can be seen that regardless of the shape of the wood chips, the slag15 mixed material with a large amount of BFSFP had a higher rate of reduction in deviator stress due to wood chips being mixing in than the slag4 mixed material. Also, it was found that the decrease rate of the deviator stress was remarkable when fibrous cocopeat was mixed in. When the solidification strength of the slag was small, the solidification strength did not decrease even when wood chips were mixed in. In other words, when the solidification strength of the material increased, the solidification strength could be reduced by mixing in wood chips. When the steel slag hardens, it is a problem that the shear strength cannot be controlled. In this study, it was found that it could be controlled by introducing wood chips.

Figure 13 shows the relationship between the normalized axial strain $\varepsilon_0$ of $\varepsilon_{50,\text{Slag}}$ and the cocopeat mixing ratio. $\varepsilon_0/\varepsilon_{50,\text{Slag}}$ is the value obtained by dividing the $\varepsilon_0$ of the cocopeat mixed material by the $\varepsilon_{50,\text{Slag}}$ of the slag with the same amount of BFSFP and the same curing period. As visible in Figure 13, at a cocopeat mixing ratio of 5 vol%, there was no significant difference between the $\varepsilon_0/\varepsilon_{50,\text{Slag}}$ of slag4 mixed and that of the slag15 mixed material. At a cocopeat mixing ratio of 10 vol%, the mixed material of cocopeat and slag4 shows an $\varepsilon_0$ that is about 3 times that of slag4 at both, 7 and 28 days of curing. There is almost no difference between the $\varepsilon_0$ of the mixed material consisting of cocopeat and slag15 and the $\varepsilon_0$ of slag15. In addition, at a cocopeat mixing ratio of 33 vol%, $\varepsilon_0/\varepsilon_{50,\text{Slag}}$ was greatly increased regardless of the amount of BFSFP present and the curing period.

Figure 14 shows the relationship between the normalized axial strain $\varepsilon_0$ of $\varepsilon_{50,\text{Slag}}$ and the hinoki mixing ratio. From Figure 14 it can be seen, that, when cocopeat was mixed with slag4, the $\varepsilon_0/\varepsilon_{50,\text{Slag}}$ increased linearly with the increase in the mixing ratio of hinoki. In contrast, when hinoki was mixed with slag15, the $\varepsilon_0/\varepsilon_{50,\text{Slag}}$ hardly changed, even if the mixing ratio of hinoki increased. Also, as can be seen in Figures 13 and 14, at a the hinoki mixing ratio of 33 vol%, the increase of $\varepsilon_0$ was not as great as that of the cocopeat mixing ratio of 33 vol%. Additionally, if the shape of the wood chips, the amount of BFSFP, and the mixing ratio of the wood chips are the same, it was found that the $\varepsilon_0/\varepsilon_{50,\text{Slag}}$ hardly changed even with different curing periods.

To summarize the results above, it is possible to reduce the stiffness and increase the failure strain by adding fibrous wood chips. Additionally, when adding granular wood chips, it was found that a relatively large amount of wood chips had to be mixed in to obtain the same effect. In solidified ground materials, the problems are the brittleness and the excessive stiffness. So, in this study, it was found that the introduction of wood chips may reduce these properties.

4 CONCLUSIONS

In this paper, CD tests were performed to understand the effects of the amount of BFSFP introduced, and the
The deviator stress of slag15 shows a greater axial stress than slag4 (no wood chips mixed in), regardless of the types of wood chips and the curing periods.

2) In the case of the sample of slag15 mixed with wood chips, the shear strength decreases with an increase in the ratio of wood chips, regardless of the type of wood chips and the curing periods.

3) The deviator stress of slag15 mixed material is larger than that of slag4 mixed material, regardless of the types and mixing ratios of the wood chips. Additionally, in the case of the sample of slag15, the rate of decrease of the deviator stress after the shear strength is slows down. That is, the sample of slag15 shows brittle behavior.

4) In the material mixed with slag15, $\varepsilon_{50}$ does not change significantly when the mixing ratio of cocopeat is 10 vol% or that of hinoki is 33 vol%. On the contrary, even if slag15 is mixed with cocopeat at 33 vol%, $\varepsilon_{50}$ becomes extremely large.

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