Effects of wood chips types and mixing ratio to the compression characteristics of steelmaking slag mixed with wood chips

Tomotaka Yoshikawa
Tokyo University of Science, Chiba, Japan. E-mail: 7619703@ed.tus.ac.jp

Yoshiaki Kikuchi
Tokyo University of Science, Chiba, Japan. E-mail: kikuchi_y@rs.tus.ac.jp

Shohei Noda
Tokyo University of Science, Chiba, Japan. E-mail: s-noda@rs.tus.ac.jp

Keywords: fibrous wood chips, steelmaking slag, geo-materials, unconfined compression characteristics

ABSTRACT: Under-sieve residue, a type of disaster waste generated by earthquakes and tsunamis, contain large amounts of wood chips. This residue cannot be used as ground material mainly because its bearing capacity is insufficient and the decay process of wood chips has not been well understood. In this study, unconfined compression (UC) tests were performed using two types of wood chips (fibrous cocopeat and granular hinoki), which closely resemble the under-sieve residue, with slag and Iwaki sands. The test results indicated that the UC strength of the slag mixed with cocopeat or hinoki at 10% by volume was higher than that of only slag. In addition, they indicated that the UC strength and deformation modulus of Iwaki sand mixed with cocopeat were higher than those of just Iwaki sand for cocopeat mixing ratios of less than 20% by volume.

1. INTRODUCTION

A large amount of disaster waste was generated in the aftermath of the 2011 off the Pacific coast of Tohoku Earthquake in eastern Japan and the July 2018 Torrential rain in western Japan. Under-sieve residue was generated as one of the disaster wastes and is primarily composed of wood chips. However, it cannot be used owing its low bearing capacity and lack of understanding of the effects and process of wood chip decay. Under-sieve residue is a sediment fraction obtained using a vibrating and rotating sieve machine that has been set to a sieve size of 20 mm or less. This results in large variations in the shape and size of the wood chips depending on the disposal site where this residue was obtained from.

Steelmaking slag is an industrial by-product of crude steel. Each year, large quantities of slag are produced by the steel manufacturing industry. This steelmaking slag has hydraulic solidification properties (Tuboi et al., 1974 and Karamacharya et al., 1979) that cause this slag to react with water that results in a material that exhibits excellent wear resistance after a curing process (Inui et al., 2012). These hydraulic solidification properties of steelmaking slag can be utilized to devise an effective method that uses the under-sieve residue and converts it into ground materials. This could ensure a good disposal method for disaster waste and aid in the rapid recovery in the aftermath of a disaster.

Various studies on composite ground materials (Mori et al., 2003 and Nonoyama et al., 2011) have been conducted to date. However, there are not many studies on mixed materials in which a large amount of compressible and fibrous materials such as wood chips are mixed. The authors hypothesized that the wood chips in the under-sieve residue have a significant effect on the mechanical properties of the under-sieve residue. Therefore, the shear characteristics of a material that contains mixed wood chips and steelmaking slag were experimentally examined. (Yoshikawa et al., 2018b). It was found that the increase in the strength of material owing to the curing process decreases

P. Duc Long and N. T. Dung (eds.) et al., *Geotechnics for Sustainable Infrastructure Development*, Lecture Notes in Civil Engineering 62,
https://doi.org/10.1007/978-981-15-2184-3_96

with an increase in the mixing ratio of wood chips. Thus, the studied material had sufficient strength to be considered as an effective ground material. However, the study results exhibited a high level of variability, which could not be replicated. This appears to indicate that the effect of the hydraulic solidification properties of steelmaking slag is not uniform.

Two series of tests were conducted in this study. In series 1, unconfined compression (*UC*) tests were conducted using a material that consisted of wood chips of different shapes, steelmaking slag, and blast-furnace slag fine powder (*BFSFP*). This test aimed to understand the effects of different wood shapes and the mixing ratio of wood chips and slag on the UC test results. *BFSFP* helps in promoting and assisting the hydraulic solidification reaction of steelmaking slag and is therefore added to this mixture. The mixing ratio of *BFSFP* was determined based on previous studies (Yoshikawa et al., 2018c). In the series 2 tests, *UC* tests were conducted using two different types of wood chips mixed with Iwaki sand. Iwaki sand does not solidify with curing, even after several weeks. The series 2 tests were designed based on the results of series 1.

2. MECHANICAL CHARACTERISTICS OF WOOD CHIPS MIXED WITH STEELMAKING SLAG (SERIES 1)

2.1 Materials and Test Methods

In series 1 tests, three types of materials were used: wood chips, steelmaking slag without aging treatment (ρ_s = 3.35 g/cm^3, D_{50} = 0.75 mm), and BFSFP (ρ_s = 2.89 g/cm^3) as a subsidiary material, and this was mixed with ion exchanged water.

Fig. 1 shows the grain size distribution curve for the steelmaking slag that was used in the test. The uniformity coefficient U_c is observed to be 18.42 and the curvature coefficient U'_c is 0.679. Two types of wood chips were used- fibrous coconut berry (ρ_s = 0.53 g/cm^3, hereafter referred to as cocopeat) and granular hinoki (ρ_s = 0.41 g/cm^3).

Figs. 2(a) and 2(b) show the images of cocopeat and hinoki, respectively. Even though the use of only one type of wood chips would have been ideal for this study to compare the effects of shape differences in the *UC* test results of these mixed materials, different types of wood chips were used because a suitable crusher could not be found. Cocopeat is a fibrous organic substance that constitutes the outer shell of a coconut and is often used as a ground cover material. The cocopeat wood chips used in this study had a diameter ranging from 0.1 to 0.4 mm and a maximum length of 40 mm. Hinoki is a conifer, native to Japan and Taiwan, which was crushed into a granular form of wood chips.

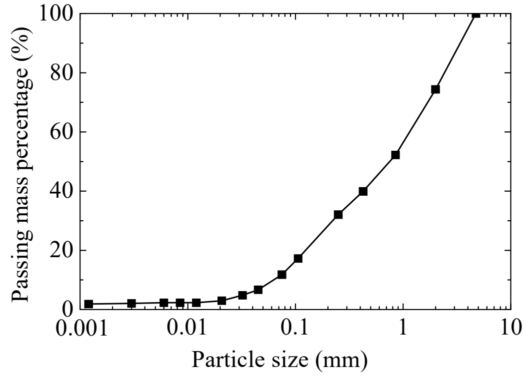
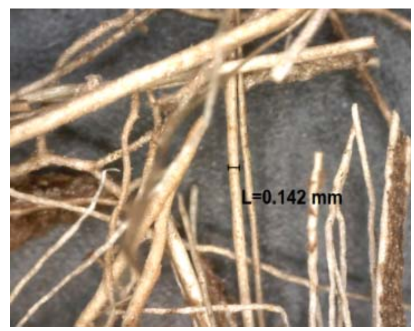
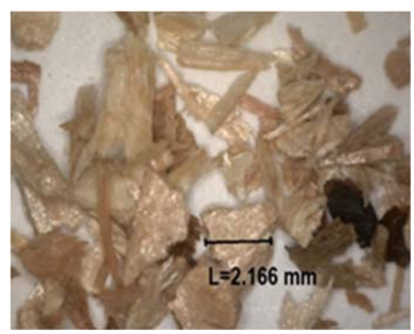


Figure 1. Grain size distribution curve of steelmaking slag



a. Cocopeat (Fibrous)



b. Hinoki (Granular)

Figure 2. Wood chips images

Fig. 3 shows an image of the steelmaking slag. It is evident that the steelmaking slag has an angular shape. The steelmaking slag used in this study was primarily composed of CaO, SiO_2, FeO+Fe_2O_3, MgO, and Al_2O_3. Because steelmaking slag contains Fe and Mg, its particle density (ρ_s = 3.35 g/cm^3) is higher than that of general soil (ρ_s = 2.6 to 2.8 g/cm^3).

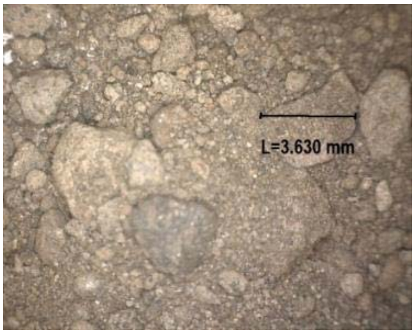


Figure 3. Steelmaking slag image

Fig. 4 shows the results of the compaction tests (A-b method) conducted prior to the *UC* tests. From previous studies (Yoshikawa et al., 2018a), the authors determined that it is difficult to compact these materials and a clear peak does not appear on the compaction curve; therefore, only one or two samples were tested under each condition. The "Only Slag" test sample, referred to in Fig. 4, is the mixture of steelmaking slag and *BFSFP* with a mass ratio of 96: 4.

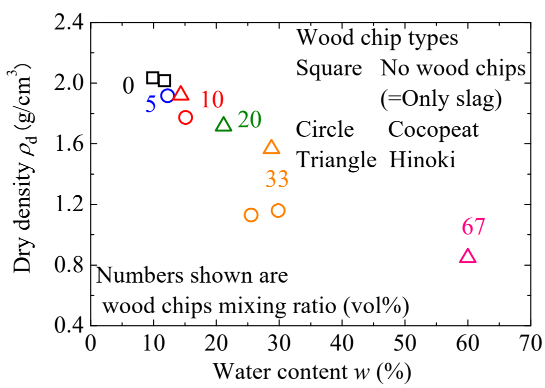


Figure 4. Compaction curves of slag with different mixing ratio of wood chips

Table 1 lists the specimen preparation conditions that were used to prepare the test samples. The target dry density ρ_d in Table 1 was calculated by multiplying the maximum dry density obtained from Fig. 4 by the degree of compaction, D_c, of 95%. The water content ratio, w, represents the ratio of the samples prior to the over-compaction process. It should be noted that the compaction tests were not conducted for the cocopeat mixing ratios of 15%, 20%, and 27% by volume owing to the lack of steelmaking slag. Therefore, ρ_d and w for these conditions were calculated by linearly interpolating the data obtained for the cocopeat samples with a mixing ratio of 0%, 5%, 10%, and 33% by volume.

The samples were manufactured using a five-layer tamping method that utilized a hollow cylindrical mold with a diameter and height of 50 and 100 mm, respectively. Each specimen was sealed and then cured at a constant temperature of 20 °C. *UC* tests were conducted on the specimens after their prescribed curing periods. In the *UC* test, each specimen was compressed after draining all water at an axial strain rate of 1%/min. The *UC* tests were repeated three times under the same mixing conditions. However, for some conditions, only one test was conducted, the reasons for which will be discussed later in this paper.

Table 1. Specimen Preparation Conditions (Series 1)

Wood chips types	Mixing ratio (vol%)	Target dry density ρ_d (g/cm^3)	Water content ratio w (%)
(Only Slag)	0	1.92	12.0
Cocopeat	5	1.82	13.0
	10	1.69	14.7
	15	1.56	16.5
	20	1.42	20.2
	27	1.24	22.4
	33	1.07	25.0
Hinoki	10	1.82	14.3
	20	1.63	21.1
	33	1.45	25.0
	67	0.81	60.0

2.2 *Effects of Types of Wood Chips and Mixing Ratios on Unconfined Compression Characteristics*

Fig. 5 shows the relationship between axial stress σ and axial strain ε_a obtained from the *UC* tests with fibrous cocopeat mixing ratios of 0%, 5%, 10%, 15%, 20%, 27%, and 33% by volume. The circles on each plot indicates the value of the *UC* strength, q_u, for each sample. In addition, the test result (0 vol%) for the "Only Slag" material is also shown for comparison purposes. It should be noted that for the samples containing a cocopeat mixing ratio of 10%, 15%, and 20% by volume, only one test was conducted. For the remaining mixing ratio samples, three tests were conducted, which yielded excellent repeatability. Owing to the low variability in the test results for these samples, the results from only one test has been shown in the figure for these mixing ratios. The results indicate that the rigidity decreases with the increasing mixing ratio of fibrous cocopeat. However, when compared to the "Only Slag" sample, both q_u and failure strain ε_f increased and the rigidity decreased for the samples with a cocopeat mixing ratio of 5%, 10%, and 15% by volume.

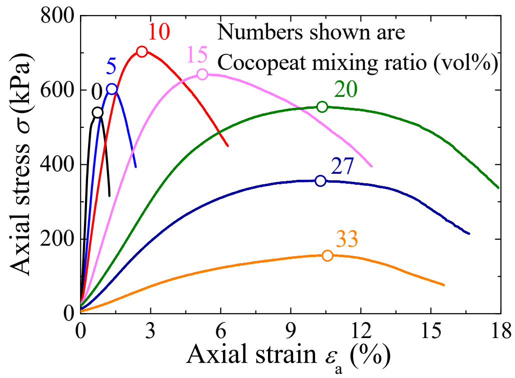


Figure 5. σ-ε_a curves of slag mixed with cocopeat

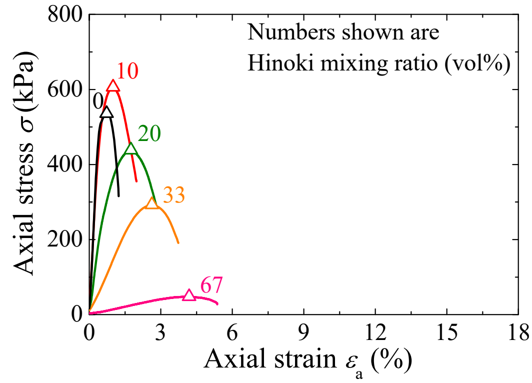


Figure 6. σ-ε_a curves of slag mixed with hinoki

Fig. 6 shows the relationship between axial stress, σ, and axial strain, ε_a, obtained from the *UC* tests conducted on the samples with granular hinoki wood chips mixed with slag, with mixing ratios of 0%, 10%, 20%, 33%, and 67% by volume. For each sample, the UC tests were conducted three times and the variability in the test results was found to be small. Therefore, the results from only of the tests has been presented as the representative result. It is evident from the results presented in Fig. 6 that when compared to the "Only Slag" sample, only the 10% by volume hinoki wood chip slag sample had rigidity that was almost equal and the q_u value was higher. The q_u and stiffness decreased for the remaining hinoki wood chip samples. In comparison to slag mixed with fibrous cocopeat, the hinoki samples showed a remarkably large rate of decrease in the stress after the peak strength value had been attained. The *UC* tests have no restraining pressures and hence, the decrease in stress after the peak strength is remarkable. The same tendency is seen in general soil material, as was observed in the solidified material mixed with hinoki. Samples that contained cocopeat had a more moderate rate of decrease in stress after the peak strength point had been attained. The authors theorize that cocopeat fibers exhibited pull-out resistance inside the specimen, which prevented the rapid collapse of the specimen.

Fig. 7 shows the relationship between the *UC* strength q_u and the mixing ratio of wood chips, using data from all the conducted tests. Irrespective of the shape and nature of the wood chip, it was observed that q_u increases with the increase in wood chips mixing ratio, up to a value of 10% by volume, following which, the increased wood chip volume ratio leads to a decreasing value of q_u. Further it can be noted that:

- at a mixing ratio of 20% by volume, cocopeat mixed samples had a higher value of q_u than the hinoki wood chip mixed samples;
- but at a mixing ratio of 30% by volume mix ratio, the results were reversed, with the hinoki wood chips showing a higher q_u value than the corresponding cocopeat sample.

As shown here, q_u of slag decreased with mixing cocopeat more than by 30% volume when the q_u of slag itself is around 500 kPa.

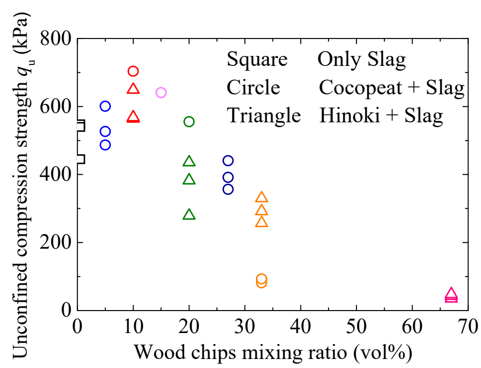


Figure 7. Relationship between q_u and wood chips mixing ratio

Fig. 8 shows the relationship between the deformation modulus E_{50} and the mixing ratio of wood chips. The deformation modulus E_{50} (MPa) is calculated as

$$E_{50} = (q_u / 2) / \varepsilon_{50} \tag{1}$$

where ε_{50} (%) represents the axial strain when the axis stress has a value of $q_u/2$. Fig. 8 shows the results of all tests that have been conducted in this study. It is evident that the parametric value of E_{50} decreases with the increase in wood chips mixing ratio, except for the sample with hinoki wood chips at a mixing ratio of 10% by volume. The trend for both types of wood chips has been observed to be similar. It was also observed that for the same mixing ratio of wood chips, the E_{50} parameter value is lower for the samples containing cocopeat in comparison to those with the hinoki wood chips.

These results indicate that the addition of an appropriate amount of wood chips to the slag can result in sample materials with a higher value of q_u than can be obtained from slag material without any added wood chips. A more careful examination of the data indicates that if the goal is to increase q_u of the slag material, mixing a moderate amount of fibrous wood chips instead of granular wood chips would be more effective. However, if the goal is to increase the rigidity of the material, mixing granular wood chips instead of fibrous wood chips would be more effective.

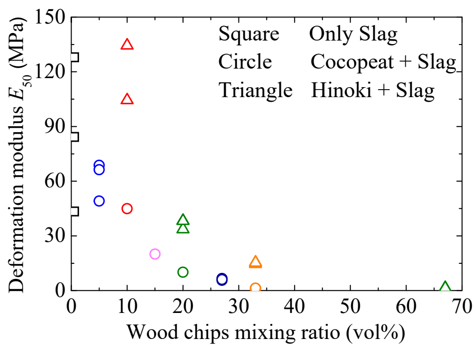


Figure 8. Relationship between E_{50} and wood chips mixing ratio

3. MECHANICAL CHARACTERISTICS OF WOOD CHIPS MIXED WITH IWAKI SAND (SERIES 2)

The series 1 tests indicated that the *UC* strength of slag mixed with an appropriate amount of cocopeat or hinoki was higher than that of slag with no wood chips ("Only Slag" material). In the series 2 tests, *UC* tests were performed using a mixture of Iwaki sand and wood chips to understand if the *UC* strength was dependent on the mixing ratio of the wood chips when the specimen does not harden, similar to the case of slag material.

3.1 Materials and Test Methods

In series 2 tests, two types of materials were used: wood chips (similar to series 1 tests) and Iwaki sand (ρ_s = 2.67 g/cm^3, D_{50} = 0.75 mm) mixed using ion exchanged water.

Fig. 9 shows the grain size distribution curve for steelmaking slag used in the series 1 tests. Iwaki sand used in these tests was sieved using a sieve size of ♯0, 1, S3, 3, 4, and 7 to create sand samples with varying grain sizes. By mixing these sets of sieved Iwaki sand in an appropriate ratio, the particle size of the Iwaki sand samples used for the testing was ensured to be similar to that of the steelmaking slag used in series 1 tests. For particles smaller than 0.075 mm in diameter, sedimentation analysis was used (JIS A 1204).

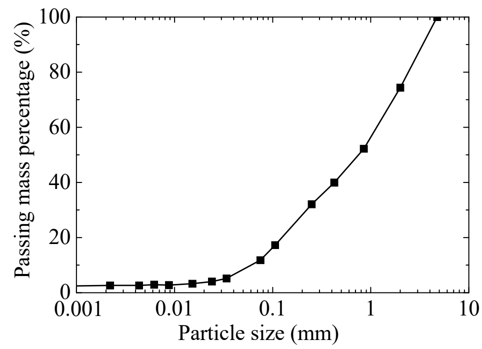


Figure 9. Grain size distribution curve of Iwaki sand

Fig. 10 shows an image of Iwaki sand. Iwaki sand was selected for the tests in series 2 because these sand grains have a similar shape to the grains of steelmaking slag, and this study aimed to use material that resembled the shape of slag but could not solidify.

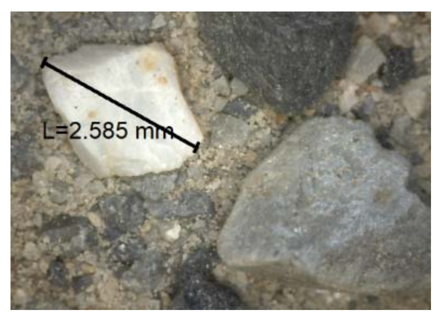


Figure 10. Iwaki sand

Fig. 11 shows the results of the compaction tests (A-b method) with Iwaki sand, cocopeat, or hinoki mixing ratio of 33% by volume.

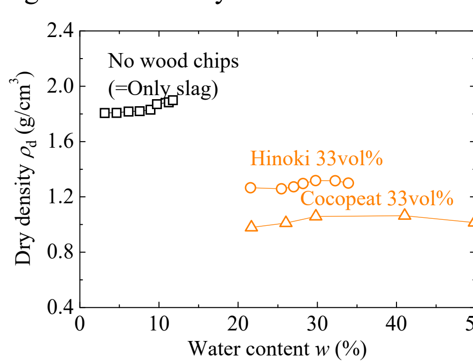


Figure 11. Compaction curves of Iwaki sand with different mixing ratios of wood chips

Table 2 lists the specimen preparation conditions used for the series 2 tests. The target dry density ρ_d in Table 2 was calculated by multiplying the maximum dry density obtained from Fig. 4 by the degree of compaction D_c = 95%. ρ_d and w of the cocopeat mixing ratio of 5, 10, and 20 vol% were calculated by linear interpolation from the test results of the cocopeat mixing ratio of 0 and 33 vol%. Similarly, ρ_d and w of the hinoki mixing ratio of 10% and 20% by volume were calculated by linear interpolation from the test results of the hinoki mixing ratio of 0% and 33% by volume.

Table 2. Specimen Preparation Conditions (Series 2)

Wood chips types	Mixing ratio (vol%)	Target dry density ρ_d (g/cm^3)	Water content ratio w (%)	Degree of saturation S_r (%)
(Iwaki sand)	0	1.78	9.7	52.0
Cocopeat	5	1.66	12.2	58.0
	10	1.53	14.7	60.0
	20	1.28	19.6	58.5
	33	0.96	26.0	47.5
Hinoki	10	1.60	14.5	67.0
	20	1.43	19.3	78.0
	33	1.20	25.5	81.5

3.2 Effects of wood chips mixed with Iwaki sand on unconfined compression characteristics

This series of tests did not assume an increase in the *UC* strength q_u due to solidification. The *UC* tests were also conducted seven days after the curing periods. No significant differences were found in the comparison results for the samples that were not cured. This work attempted to ensure that there was no increase in q_u due to the plastic mold restraint during the seven days of curing.

Fig. 12 shows the relationship between axial stress σ and axial strain ε_a obtained from the *UC* tests with fibrous cocopeat mixing ratios of 0%, 5%, 10%, 20%, 33%, and 67% by volume. The test result of Iwaki sand with no wood chips (0% by volume) is also shown for comparison. The *UC* tests were conducted three times for all conditions and the variations in the test results were found to be small. Therefore, only the representative result is shown in the figure. The circle indicates the location of the *UC* strength q_u for each sample. From Fig. 12, the value of q_u after mixing the cocopeat is significantly higher than that of Iwaki sand, irrespective of the cocopeat mixing ratio. It is observed that the q_u of cocopeat mixing ratio of 20 vol% is approximately 20 times that of Iwaki sand. In addition, the increase in failure strain ε_f is significant between the cocopeat mixing ratios of 10% and 20% by volume. It is theorized that the increase in q_u is due to the mixing of fibrous cocopeat, thereby resulting in an increase in the pullout resistance due to interparticle suction. It is evident from the data in Table 2 that for a cocopeat mixing ratio up to 10% by volume, the degree of saturation tends to increase with the increase in wood chips mixing ratio. In general, it can be said that for specimens produced under the same conditions, the suction decreases as the degree of saturation increases. However, it is difficult to evaluate the influence of suction in these tests because the degree of saturation and mixing ratio of cocopeat are different.

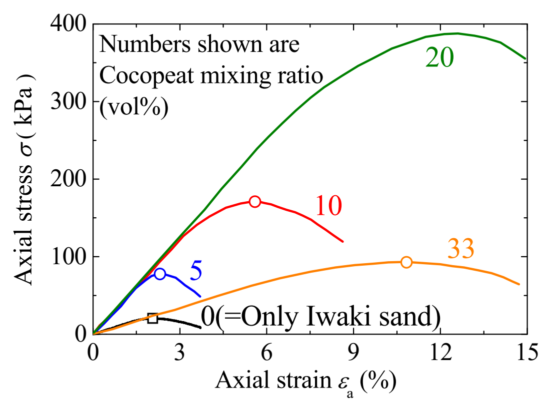


Figure 12. σ-ε_a curves of Iwaki sand with different mixing ratios of cocopeat

Fig. 13 shows the relationship between axial stress σ and axial strain ε_a obtained using the *UC* tests on the samples with granular hinoki mixing ratios of 0%, 10%, 20%, and 33% by volume. The *UC* tests were repeated three times for all samples and once again, the variations in the test results were small and therefore, only one representative result has been shown in this paper. From Fig. 13, the value of q_u for all samples with hinoki wood chips is observed to be lower than that of only Iwaki sand. The authors hypothesize that this is because pulling resistance is not exerted between the particles due to the hinoki's granular shape.

Fig. 14(a) shows the appearance of the samples at the completion of the *UC* tests of Iwaki sand. Fig. 14(b) shows the image of Iwaki sand and cocopeat at a mixing ratio of 20% by volume, and Fig. 14(c) shows Iwaki sand with hinoki wood chips at a mixing ratio of 20% by volume. A shear band can be observed in Fig. 14(b) in the horizontal direction, probably due to an eccentric load acting on the specimen owing to load shaft eccentricity. In Figs.

14(a) and 14(c), the shear band can be seen in both vertical and diagonal directions. It can be inferred from these images that there was a similar failure mechanism for both Iwaki sand and the sample with

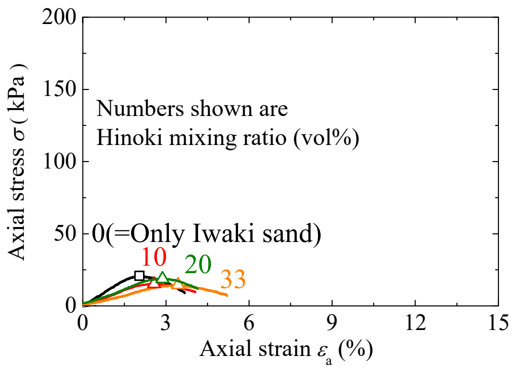
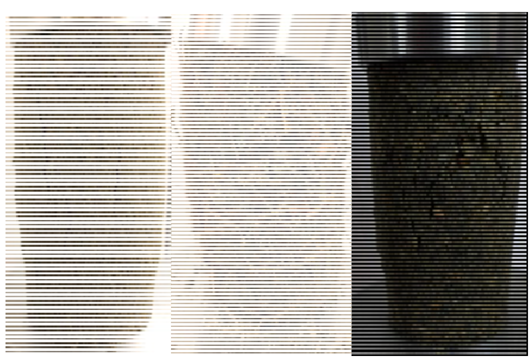


Figure 13. σ-ε_a curves of Iwaki sand with different mixing ratios of hinoki

Iwaki sand and hinoki wood chips mixed at a ratio of 20% by volume. The failure mechanism was different for the sample of Iwaki sand with cocopeat at a mixing ratio of 20% by volume.



a. Only Iwaki sand b. Cocopeat 20 c. Hinoki 20

Figure 14. Images of only Iwaki sand, Cocopeat 20 vol%, and Hinoki 20 vol% at the end of the tests

Fig. 15 shows the relationship between the *UC* strength q_u and mixing ratio of wood chips, using data from all tests performed in this series. It is evident in this figure variation among the repetitive test results (n = 3) is small for each test condition. The data clearly indicate that irrespective of the mixing ratios of wood chips, q_u for the samples with fibrous cocopeat was higher than those with granular hinoki wood chips.

Fig. 16 shows the relationship between the deformation modulus E_{50} and mixing ratio of wood chips. It is evident from this figure that E_{50} has a much higher variation in the repetitive tests done for the samples with a mixing ratio of 5%. However, the variation was minimal for the repetitive tests in for samples with higher mixing ratios. Irrespective of the mixing ratio of wood chips, E_{50} of the fibrous cocopeat samples is larger than that of samples with hinoki wood chips.

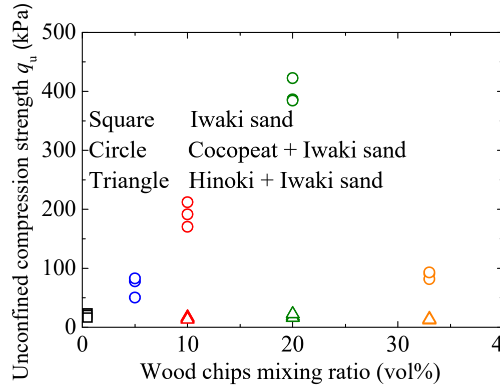


Figure 15. Relationship between q_u and wood chips mixing ratio

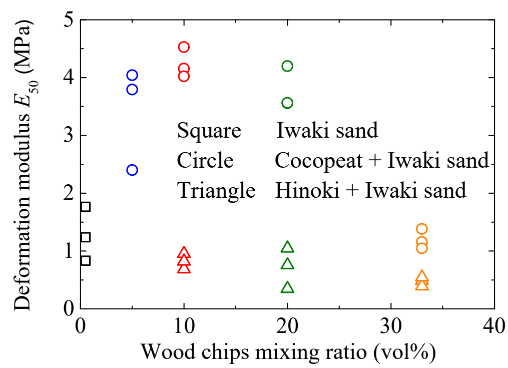


Figure 16. Relationship between E_{50} and wood chips mixing ratio

On comparing the stress-strain curves in Fig. 5 for series 1 tests to those in Fig. 12 for series 2 tests, it can be inferred that the influence of the hydraulic solidification reaction is larger when the cocopeat mixing ratio is 20% by volume or less, and the influence is much smaller when the cocopeat mixing ratio exceeds 20% by volume.

Similarly, on comparing the deformation modular results for the series 1 tests shown in Fig. 8 to the data for the series 2 tests shown in Fig. 16, it was observed that the deformation characteristics of the mixed material differs depending on the material mixed with wood chips.

4. CONCLUSIONS

In the first series of tests conducted in this study, the effects of differences in the shape and mixing ratio of wood chips on unconfined compression properties were determined experimentally using two types of wood chips (fibrous cocopeat and granular hinoki), steelmaking slag, and *BFSFP*. In the second series of tests, the same tests were repeated using Iwaki sand and the same wood chips that were used in series 1 tests. The key findings obtained of this study are as follows:

- When slag (steelmaking slag mixed with *BFSFP*) is mixed with cocopeat, with mixing ratios ranging from 5% to 20% by volume, the deformation modulus decreases but the *UC* strength increases in comparison to the samples that only had slag and wood chips.
- In the samples of slag mixed with hinoki (10% by volume), the deformation modulus was similar to that of the base sample that only contained slag but the *UC* strength was slightly larger.
- For samples that had the same mixing ratio of wood chips, slag mixed with cocopeat had a smaller decrease in stress from the peak strength location than the samples with hinoki.
- The *UC* strength increased in samples that were composed of Iwaki sand mixed with fibrous cocopeat, possible owing to the increase in the pullout resistance of the cocopeat fibers.
- For samples with a mixture of Iwaki sand and granular hinoki, the *UC* strength and deformation modulus were almost equal to those obtained in the Iwaki sand sample. This implies that mixing granular hinoki with materials that do not solidify like Iwaki sand does not result in increased pull-out resistance.

In future work, the factors of the increase in the *UC* strength will be examined by mixing fibrous cocopeat on the *CD* tests. The authors would like to evaluate the pullout resistance of cocopeat and examine the influence of suction. In addition, it would also be worthy to determine the mechanical characteristics when changing the shape and mixing ratio of wood chips using high strength slag, which has higher hydraulic solidification reactivity than the slag used in this test.

5. ACKNOWLEDGEMENTS

This research was supported by the Steel & Slag Association and the Obayashi Foundation. The authors express their appreciation for their support.

6. REFERENCES

Inui, T., Yasutaka, T., Endo, K., and Katsumi, T. (2012). Geo-environmental issues induced by the 2011 off the Pacific Coast of Tohoku Earthquake and tsunami, *Soils and Foundations*, Vol. 52, No. 5, pp 856–871.

Karamacharya, M.R., Uchida. I., and Idemitsu, T. (1979). On the studies of utilisation of converter furnace slag in road bases. *Journal of Japan Society of Civil Engineers*, (282), pp 101–113 (in Japanese).

Nonoyama, H., Nakano, M., Araki, T., and Hamajima, K., (2014). Mechanical behavior of soil-wood chip mixtures generated from earthquake waste. Proceeding of the 7th International Congress on Environmental Geotechnics, pp 527–532.

Mori, M., Takahashi, H., Ousaka, A., Horii, K., Ishii, T., and Kotani, K. (2003). A proposal of new recycling system of high-water content mud by using paper debris and polymer and strength property of recycled soils. *The Mining and Materials Processing Institute of Japan*, Vol. 119, pp 155–160 (in Japanese).

Oobayashi, S., Kikuchi, Y., Hyodo, T., Mutoh, M., and Saitoh, S. (2015). Strength characteristics under seawater environment of geo-material mixed with refined steel making slag. *Journal of Japan Society of Civil Engineers, Ser. B3(Ocean Engineering)*, Vol. 71, pp 1167–1172 (in Japanese).

Tuboi, T., Kimijima, T., and Koide, Y. (1974). Solidification property of converter steelmaking slag. *The Annual Report of Cement and Concrete Engineering*, Vol. 28, pp 98–103 (in Japanese).

Yoshikawa, T., Kikuchi, Y., Hyodo, T., Kakihara, Y., Iwai, D., and Kaneda, T. (2018a). Influence of differences in fine-grained slag content on hydraulic solidification of converter steelmaking slag. *Proceedings of the 17th Global Joint Seminar on Geo-Environmental Engineering*, pp 169–174.

Yoshikawa, T., Kikuchi, Y., Hyodo, T., Obayashi, S., Kakihara, Y., Iwai, D., and Kaneda, T. (2018b). The effect of aging treatment on the mechanical properties of steelmaking slag mixed with crushed slag. *New Advances in Geotechnical Engineering*, *ISBN 978-7-114-13956-7*, pp 410–415.

Yoshikawa, T., Kikuchi, Y., Noda, S., Kakihara, Y., Oshikawa, R., and Oshino, A. (2018c). Unconfined compression strength of converter steelmaking slag mixed with subsidiary solidifying materials. *Research Presentation of The 15th Kanto Branch of Japanese Geotechnical Society*, pp 298–301 (in Japanese).