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Effective utilization of incineration bottom ash as geomaterial by combining carbonation treatment and specific gravity sorting

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ABSTRACT: In Japan, approximately 4 million tons of Municipal Solid Wate Incineration Bottom Ash (MSWIBA) is landfilled in final disposal sites. Effective utilization of IBA is required to extend the lifespan of the final disposal sites. IBA is effectively used in Europe as base-course material and embankment material since it has a grain size distribution similar to sandy soil. However, IBA tends to exceed the Japanese soil environmental standard values, and the standard values based on the Soil Contamination Countermeasures Law in terms of Pb leaching and content. Therefore, the development of a method to reduce Pb leaching and content is the most important issue for the conversion of IBA into civil engineering materials. In this study, carbonation treatment was performed to reduce the amount of Pb leaching from IBA, and the leaching properties and CO_2 fixation amount of the carbonated IBA were examined. Moreover, for the reduction of Pb content in IBA, air table sorting was examined, referring to the case study in Europe, and studied the reduction of Pb content in IBA sorted to low specific gravity by air table sorting. The physical and mechanical properties of IBA modified by a combination of carbonation treatment and air table sorting were also studied for the application of IBA to geomaterial. The results showed that IBA combined with carbonation treatment and specific gravity sorting can reduce the leaching concentration and content of Pb. In addition, it was found that IBA can fix 35 kg/t CO_2 and has sufficient mechanical properties as a geomaterial.

KEYWORDS: Incineration bottom ash, carbon fixation, specific gravity sorting.

1 INTRODUCTION

Currently, approximately 80 % of general waste in Japan is incinerated, generating about 4 million tons of incineration bottom ash (IBA) annually (Ministry of the Environment of Japan, 2025). 75% of this IBA is landfilled at final disposal sites, and new effective ways to use incinerated ash are needed to extend the life of final disposal sites. In Europe (especially in Germany and Denmark), IBA is used more effectively as a geomaterial than in Japan, and after aging treatment and physical sorting such as specific gravity sorting, it is used as base-course material, subbase layer or embankment material at disposal sites (Chen et al. 2022; Hjelmar et al. 2007). Based on these background, the objective of this study is to sort the IBA into high-density particles and low-density particles by specific gravity difference using an air table sorting machine, and to effectively use the heavy metals contained in the high-density particles as raw materials for metal recovery and refining, and the low-density particles as geomaterials such as base-course material or embankment material by carbonation treatment to immobilized heavy metals, etc., respectively.

This study describes: (1) the immobilization of Pb and CO_2 fixation by carbonation treatment of IBA, (2) reduction of Pb content in IBA by specific gravity sorting, and (3) the effective utilization of IBA modified by a combination of carbonation treatment and specific gravity sorting as geomaterials.

2 TESTING PROCEDURE

IBA discharged from the stoker furnace (sieved to a particle size of 19 mm or less) was used in the experiment; since the physical properties of IBA may vary depending on the time of discharge, IBA discharged in December 2021 and July 2022 were used in this experiment. Table 1 shows the physical properties of each IBA and Figure 1 shows the physical composition. For the physical composition, IBA was washed through a sieve with a mesh aperture of 75 μm, and the portion that passed through the sieve was considered as ash. Iron-containing materials were sorted using a magnet, and glass and ceramics were visually sorted. Sand, gravel, and nonferrous metals that could not be visually sorted were classified as others. A comparison of the physical composition of the IBA shows that ash and nonferrous metals comprise the majority of the composition in IBA. There are also some differences in the percentages of glass and ceramics. This difference in the physical composition of the ash is thought to be due to the fact that the contents of the materials to be incinerated differ depending on the time of the year (Otsuka et al. 2024).

Table 1. Physical properties of IBA 2021 and 2022.

Sample	ρ_s (Mg/m^3)	C_u	C_g	ρ_{dmax} (Mg/m^3)	w_{opt} (%)
IBA 2021	2.378	200	0.63	1.45	23.7
IBA 2022	2.465	119	9.74	1.50	22.0

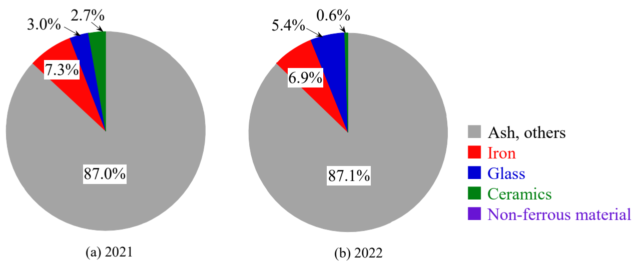

Figure 1. physical composition of IBA 2021 and 2022.

3 THE EFFECT OF CARBONATION TREATMENT ON LEAD IMMOBILIZATION AND CO2 FIXATION IN IBA

3.1 *Carbonation treatment and leaching test method*

Carbonation treatment was performed using the carbonation equipment (ash filling section: 640 x 440 x 320 mm) shown in Figure 2, with CO_2 ventilated through the gas inlet at the bottom of the container. Table 2 shows the carbonation treatment conditions in this experiment. These experimental conditions

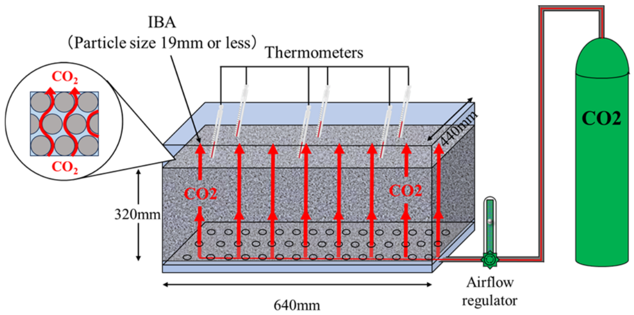

Figure 2. Carbonation treatment equipment.

Table 2. Testing conditions of carbonation treatments.

Sample	CO_2 concentration (%)	Ventilation speed (L/min)	Ventilation time (h)	Amount of IBA (kgDW)	Water content (%)	Filling density (g/cm³)	CO_2 Amount (g/kgDW)
IBA 2021	100	30	1.5	69.0	30.6	1.00	90
IBA 2022					29.7		

were set with reference to past research results (Fujikawa et al. 2023). IBA with a natural water content (approximately 30 %) was used to investigate the immobilizing effect of carbonation treatment on Pb, Japanese Leaching Test No.46 (Notification No. 46 by the Ministry of Environment, Japan, JLT 46) was conducted on the IBA before and after carbonation. IBA that passed through a 2 mm sieve was shaken for 6 hours at a liquid-solid ratio of 10 and then filtered and centrifuged to prepare a test solution. The pH of the test solution was then measured and the concentration of Pb eluted was determined. The concentration of Pb was measured after measuring the pH of the test solution. Cr(VI) which may be solubilized by carbonation treatment, was also measured under various conditions.

3.2 *CO_2 fixation measurement method*

To quantify the amount of CO_2 immobilized by carbonation treatment, the CO_2 gas pressure generated by the reaction between carbonate and hydrochloric acid in IBA was measured using the gas pressure measuring device shown in Figure 3 (Fukue et al. 2001; Saito et al. 2022). Considering that IBA contains a variety of substances, 20 ml of 3 mol/L hydrochloric acid was reacted with 5.0 g of IBA in a flask. The gas pressure generated was considered to be due to the decomposition of carbonate, and the $CaCO_3$ content was calculated from the calibration curve using $CaCO_3$ shown in Figure 4. The same value was then substituted into Equation 1 below, and the CO_2 fixation amount was calculated from the difference between the pre- and post-carbonate chloride samples.

$$M_{CO_2} = m_{CaCO_3} \times \frac{MW_{CO_2}}{MW_{CaCO_3}} \times \frac{1}{m_{ash}} \quad (1)$$

where M_{CO2}: amount of CO_2 fixed (kg_{CO2}/t_{Ash}), m_{CaCO3}: calcium carbonate content (g), MW_{CO2}: molecular weight of CO_2,

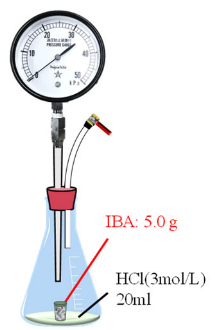

Figure 3. Gas pressure measuring device.

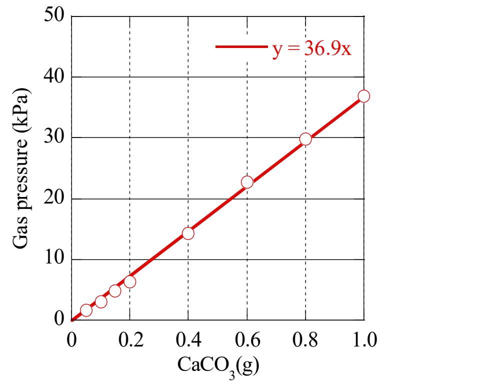

Figure 4. Calibration curve of method for determining $CaCO_3$ content in a material.

Table 3. Batch leaching test results of IBA2021 (JLT46).

Sample	pH	Pb (mg/L)	Cr(VI) (mg/L)
2021 IBA 1	11.9	0.05	N.D.
2021 IBA 2	11.9	0.06	N.D.
2021 IBA 3	11.7	0.15	N.D.
2021 Carbonated IBA 1	10.9	N.D.	N.D.
2021 Carbonated IBA 2	10.6	N.D.	N.D.
2021 Carbonated IBA 3	10.8	N.D.	N.D.
Soil environmental standard in Japan		<0.01	<0.05
Lower limit of quantification in this experiment		0.01	0.02

Table 4. Batch leaching test results of IBA2022 (JLT46).

Sample	pH	Pb (mg/L)	Cr(VI) (mg/L)
2022 IBA 1	11.7	0.05	N.D.
2022 IBA 2	11.8	0.07	N.D.
2022 IBA 3	11.8	0.27	N.D.
2022 Carbonated IBA 1	10.8	N.D.	N.D.
2022 Carbonated IBA 2	10.7	N.D.	N.D.
2022 Carbonated IBA 3	10.7	N.D.	N.D.
Soil environmental standard in Japan		<0.01	<0.05
Lower limit of quantification in this experiment		0.01	0.02

Table 5. Results of CO_2 fixation per ton of IBA.

Sample	CO_2 fixation amount (kg_{CO2}/t_{ash})
IBA 2021	36.7
IBA 2022	34.3

MW_{CaCO3}: molecular weight of calcium carbonate, m_{ash}: mass of the main ash used (kg).

3.3 *Evaluation of Pb immobilization effect and CO_2 fixation by carbonation treatment*

Table 3 and Table 4 show the results of the leaching test for each IBA (before and after carbonation). The amount of Pb eluted from both samples after carbonation was lower than before carbonation, indicating that carbonation treatment suppresses Pb leaching. The amount of Pb leached from the IBA after carbonation satisfied the soil environmental standard under all conditions. This may be due to the decrease in pH and the formation of immobilized Pb carbonate through carbonation. On the other hand, it was thought that carbonation might increase the leaching of hexavalent chromium in some types of IBA, but in the present results, hexavalent chromium was not detected even after carbonation in this study.

Table 5 shows the amount of CO_2 fixed per ton (dry mass) of IBA. Approximately 35 kg/t of CO_2 can be fixed of IBA by carbonation treatment. Therefore, assuming that all the 3.2 million tons of IBA (2.5 million tons dry mass) emitted annually is carbonated, approximately 88,000 tons of CO_2 can be fixed in IBA annually. These results indicate that carbonation treatment of IBA has high potential to contribute to carbon neutrality.

4 REDUCTION OF LEAD CONTENT IN IBA BY SPECIFIC GRAVITY SORTING (AIR TABLE)

4.1 *Overview of Specific Gravity Sorting and Experimental Conditions*

As shown in Figure 5, the air table is a dry specific gravity sorting device that tilts a mesh-shaped table, feeds air from the bottom of the table, and adjusts the air volume, vibration frequency, side slope angle, and end slope angle to sort samples into particles of low specific gravity and particles of high specific gravity. Despite its small size, this system can continuously sort samples (dimensions of sorting section: 302 × 272 × 200 mm). In this study, this equipment was used to sort IBA 2022 into 4 pots (denoted pots 1), 2), 3), and 4)) from the low specific gravity side to the high specific gravity side, and the bulk density and Pb content of the IBA sorted into each pot were measured. Bulk density was calculated by dividing the mass of each pot after sorting by its volume in the loosely packed state. Preliminary tests were conducted by varying the water content of IBA, slope angle of air table equipment, air volume, and vibration frequency under various conditions for sorting. From the results of the preliminary tests, conditions (Table 6) were identified under which bulk density increased significantly from low to high specific gravity. IBA of low specific gravity (pot 1) and high specific gravity (pot 4) were sampled, respectively, and Pb content was measured according to the content test (Notification No. 19 by the Ministry of the Environment, Japan).

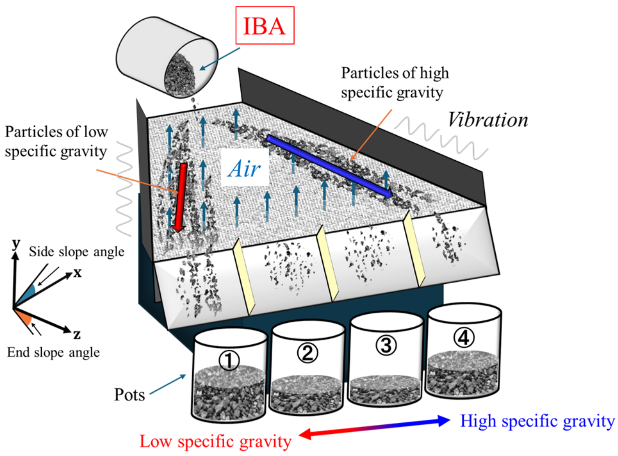

Figure 5. Appearance of specific gravity sorting device (air table).

Table 6. Testing conditions of the air table.

Water content (%)	Air voilume (m/s)	Side slope angle (°)	End slope angle (°)	Vibration frequency (Hz)
10	2.0	10		
20	2.5	13	4	28
30	3.0	13		

4.2 *Evaluation of the effect of specific gravity sorting on the reduction of Pb content in IBA*

Figure 6 shows the wet density of IBA sorted into each pot using the conditions in Table 6, organized by water content. The density of pot 1 is the lowest at all water content, and the densities increase sequentially, indicating that the material is sorted according to the difference in specific gravity. The density difference is the largest at w=20 %, and the density difference is small at w=30 %, indicating that water content is an influential factor in sorting by specific gravity. Figure 7 shows the Pb content in low specific gravity (pot 1) and high specific gravity (pot 4) at each water content. The Pb content of low specific gravity particles is lower than that of high specific gravity particles at all water content, indicating that the Pb content can be effectively reduced by specific gravity

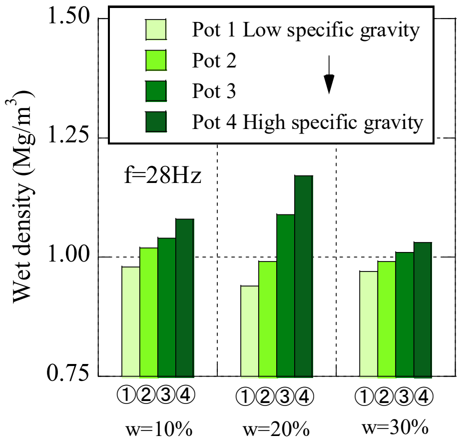

Figure 6 Wet density of IBA sorted into each pot.

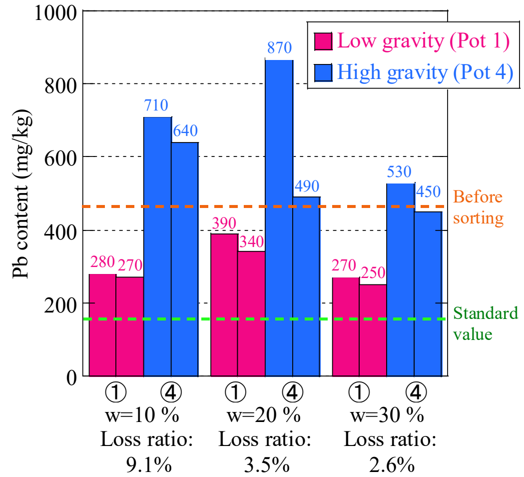

Figure 7 Pb content after sorting at each water content.

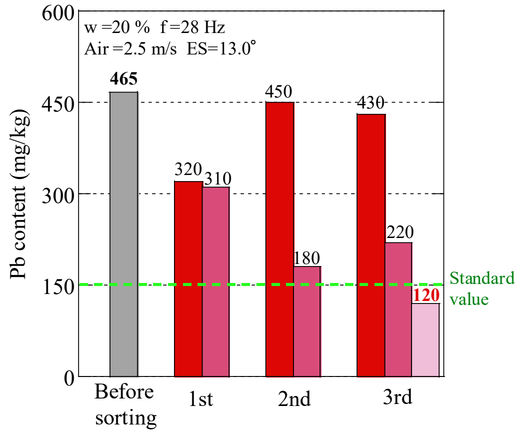

Figure 8 Relationship between the number of cycles of repeated sorting of low specific gravity IBA and Pb content.

differential sorting. The loss ratio shown in the figure refers to the rate of mass loss before and after specific gravity sorting. At a water content of 10%, the loss rate is high because the fine grains in the IBA are scattered outside the air table under the influence of the air volume, but the loss rate decreases as the water content increases. Therefore, when sorting IBA by specific gravity, a moderately water-containing state (in the present results, a water content of 20 % or higher) is considered desirable.

On the other hand, this result did not satisfy the standard value for Pb content (Pb=150 mg/kg). Therefore, this study assumed that the slope length of the air table affects the sorting efficiency, and repeatedly sorted the IBA accumulated in the low specific gravity (pot 1) as a means to compensate for the slope length. Figure 8 shows the relationship between the number of repeated sorting cycles and Pb content in low specific gravity IBA. Although there is overall variation, the Pb content tends to decrease as the number of sorting cycles increases, and results below the content standard were obtained at the third sorting cycle. This suggests that increasing the number of sorting is effective in reducing Pb content.

5 EFFECTIVE UTILIZATION OF IBA AS A GEOMATERIAL BY COMBINING CARBONATION TREATMENT AND SPECIFIC GRAVITY SORTING

5.1 *Testing procedure*

IBA 2022 was used for the experimental sample. IBA 2022 was carbonated and then sorted into low specific gravity (pot 1) by specific gravity sorting (low specific gravity-carbonated-IBA) for the experiments. The carbonation treatment was conducted under the conditions shown in Table 2, and for specific gravity sorting, sorting conditions were again selected in consideration of the changes in IBA characteristics due to carbonation treatment (Table 7). In this study, IBA before sorting (untreated-IBA), IBA with carbonation treatment only (carbonated-IBA), and IBA sorted to low specific gravity by specific gravity difference sorting (low specific gravity-IBA) were used as comparison samples. Physical sorting, density test of ash particles (JIS A 1202), particle size test (JIS A 1204), and compaction test (JIS A 1210) were conducted to determine physical properties of the low specific gravity-carbonated-IBA. Physical sorting was done by magnetic sorting to separate iron-containing materials, and visual sorting to separate glass, ceramics, and ash (including nonferrous metals, same below). Since repeated use of IBA may result in crushing of ash particles, compaction tests should normally be conducted using a non-repeatable method. However, since it is difficult to prepare a sufficient sample volume for specific gravity sorting using air table, the test was conducted using the repeated use method with a 2.5 kg rammer (A-a method). Cone index test (JIS A 1228) and Direct shear test (JGS 0560) were also conducted to investigate the applicability of the low specific gravity-carbonated-IBA to geomaterials. The cone index test was conducted on specimens prepared at optimum water content. Table 8 shows the experimental conditions for the direct shear test. For the direct shear test, a small (D=60 mm, H=20 mm) testing machine was used considering the amount of experimental specimens, and the specimens were made of IBA with a maximum grain size of 4.75 mm. The shear speed was set at 0.2 mm/min. Toyoura sand (Dr=60 %) was used as a comparison sample.

Table 7. Testing conditions of the air table (after carbonation).

Water content (%)	Air voilume (m/s)	Side slope angle (°)	End slope angle (°)	Vibration frequency (Hz)
20	2.5	11	4	28

Table 8. Experimental conditions for the direct shear test.

Testing condition	Water content	Shear speed (mm/min)	Normal applied pressure (kPa)	Maximum grain size (mm)	Relative compaction (%)
Constant pressure	Optimum water content	0.2	100 200 300	4.75	95

5.2 *Physical and mechanical properties of the low specific gravity-carbonated-IBA*

Figure 9 shows the physical composition of each condition of IBA. Comparing the composition of untreated-IBA with that of other conditions shows that the proportion of iron-containing materials with high specific gravity is lower in (b) and (c) than in (a), indicating that although sorting is effective, it is difficult to sort out iron-containing materials completely. Figure 10

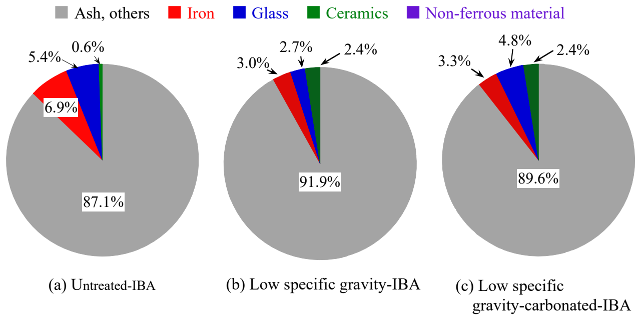

Figure 9 Physical composition of each condition of IBA.

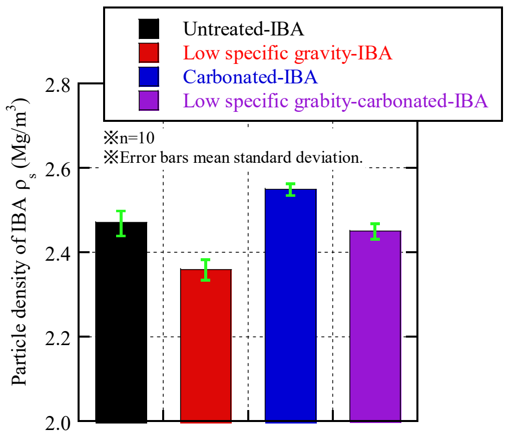

Figure 10 Particle density of each condition of IBA.

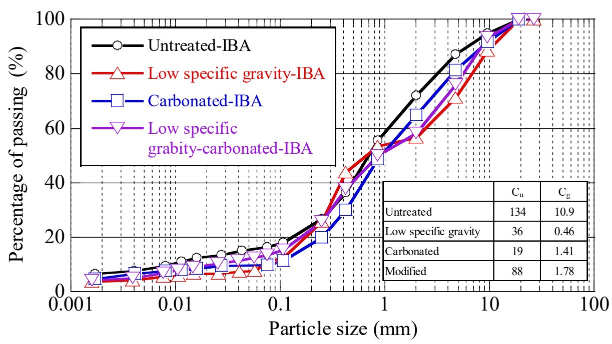

Figure 11 Grain size distribution curves of each condition of IBA.

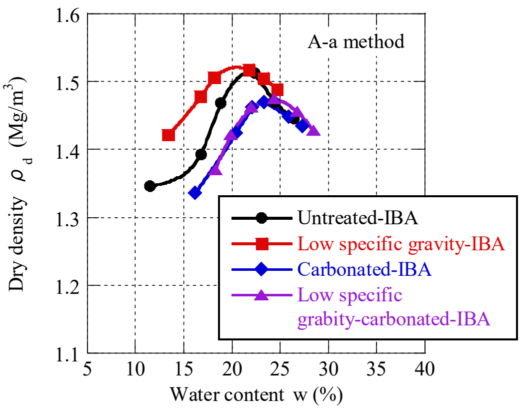

Figure 12 Compaction curve of each condition of IBA.

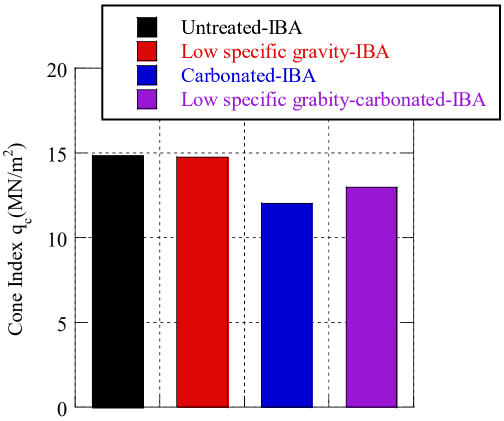

Figure 13 Cone index test results of each condition of IBA.

shows the particle density of each condition of IBA. Comparing the density of untreated-IBA and carbonated-IBA, the density of carbonated-IBA increased. This is thought to be due to the densification of the ash structure through carbonation. Figure 11 shows the grain size distribution curve of each condition of IBA. It can be seen that the grain size distribution differs depending on the carbonation process and specific gravity sorting, and that the uniformity coefficient and curvature coefficient also differ. These results indicate that carbonation and specific gravity sorting affect the grain size distribution of IBA. Figure 12 shows the compaction curve of main ash. Compared to untreated IBA, the compaction curve of carbonated IBA shifts to the lower right. This may be due to the decrease in the bonding strength between ash particles and the change in the grain size distribution as a result of carbonation (Fujikawa et al. 2020). The compaction curve for IBA sorted by specific gravity shifted to the upper left compared to the results for untreated-IBA. This may be due to the fact that IBA sorted to low specific gravity by specific gravity contain more coarse grains.

Figure 13 shows the cone index test results. Considering that the unconfined compressive strength required as an embankment material is q_u = 100 to 300 kN/m^2 and that the cone index is equivalent to approximately 5 times the unconfined compressive strength, the low specific gravity-carbonated-IBA also shows high strength, indicating that it has sufficient strength required as an embankment material. Figure 14 shows the relationship between shear stress and shear displacement, and shear displacement and vertical displacement of the low specific gravity-carbonated-IBA obtained from direct shear tests. Figure 15 shows the relationship between shear stress and shear displacement, and

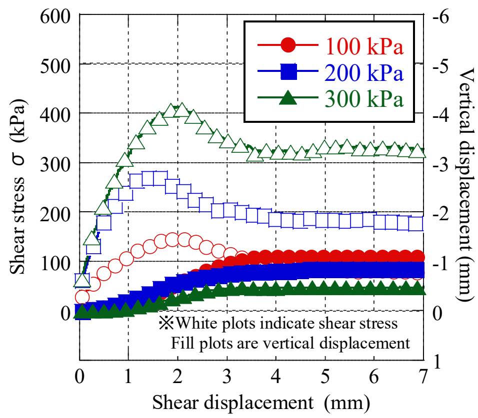

Figure 14 Relationship between shear stress and shear displacement and vertical displacement and shear displacement (Low specific gravity-carbonated-IBA).

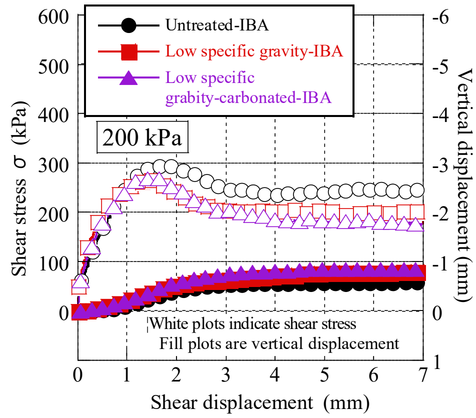

Figure 15 Relationship between shear stress and shear displacement and vertical displacement and shear displacement (Normal applied pressures: 200 kPa).

Table 9. Experimental conditions for the direct shear test.

Condition of IBA	Angle of shear resistance ϕ_d (°)	Cohesion (kN/m^2)
Untreated-IBA	53.4	5.9
Low specific gravity-IBA	54.6	0.4
Carbonated-IBA	53.4	4.0
Low specific gravity-Carbonated-IBA	39.8	0

between shear displacement and vertical displacement at 200 kPa of normal applied pressures for each condition of IBA. The white plots and filled plots in Figures 14 and 15 show shear stress and vertical displacement, respectively. It can be seen that the shear stress increases with increasing vertical stress and shows a clear peak. The vertical displacement shows a positive dilatancy, indicating that the volume expands with shear at both vertical stresses. These results indicate that the shear stress and vertical displacement of the low specific gravity-carbonated-IBA have shear behavior similar to that of dense sand. Since the stress-strain curves and peak intensities for each condition in Figure 15 are almost similar, it can be assumed that the modification treatment (a combination of carbonation and specific gravity sorting) has no adverse effect on shear properties.

Table 9 shows the angle of shear resistance and cohesion under each condition. The angle of shear resistance of the low specific gravity-carbonated-IBA is comparable to the result of the untreated-IBA, indicating that the carbonation treatment and specific gravity sorting do not affect the angle of shear resistance of the IBA. Although the angle of shear resistance may have been overestimated due to the large maximum grain size of the IBA used in this experiment, the fact that the angle of shear resistance is greater than that of Toyoura-sand suggests that the low specific gravity-carbonated-IBA is highly applicable as a geomaterial.

6 CONCLUSIONS

This study examined Pb immobilization and CO_2 fixation by carbonation treatment of IBA, reduction of Pb content in IBA by specific gravity sorting, and utilization of IBA modified by a combination of carbonation treatment and specific gravity sorting as civil engineering materials. As a result, the following conclusions were obtained.
1) Carbonation of the IBA reduces Pb leaching to below the standard value and immobilizes 35 kg/t of CO_2 in the IBA.
2) Specific gravity sorting of the IBA by air table sorting can reduce the amount of Pb contained in low specific gravity particles.
3) The IBA modified by the combination of carbonation and specific gravity sorting has mechanical properties applicable to geomaterials.

7 ACKNOWLEDGEMENTS

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