INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 3rd International Symposium on Coupled Phenomena in Environmental Geotechnics and was edited by Takeshi Katsumi, Giancarlo Flores and Atsushi Takai. The conference was originally scheduled to be held in Kyoto University in October 2020, but due to the COVID-19 pandemic, it was held online from October 20th to October 21st 2021.

Geotechnical characteristics of carbonated incineration bottom ash using exhaust and CO_2 discharged from waste incineration facilities

Takuro Fujikawa i), Kenichi Sato ii), Chikashi Koga iii), Hirofumi Sakanakura iv),
Hiroshi Kubota v) and Yosuke Nagayama vi)

i) Assistant Professor, Department of Civil Engineering, Fukuoka University, 8-19-1, Nanakuma Jonan, Fukuoka 814-0180, Japan.
ii) Professor, Department of Civil Engineering, Fukuoka University, 8-19-1, Nanakuma Jonan, Fukuoka 814-0180, Japan.
iii) Research Assistant, Department of Civil Engineering, Fukuoka University, 8-19-1, Nanakuma Jonan, Fukuoka 814-0180, Japan.
iv) Research fellow, National Institute for Environmental Studies, 16-2, Onogawa Tsukuba, Ibaraki 305-8506, Japan.
v) Research fellow, Fujita Corporation, 2025-1, Ono Atsugi, Kanagawa, 243-0125, Japan.
vi) Muster student, Department of Civil Engineering, Fukuoka University, 8-19-1, Nanakuma Jonan, Fukuoka 814-0180, Japan.

ABSTRACT

In Japan, approximately 4 million tons of incineration bottom ash (IBA) from municipal solid waste (MSW) are discharged a year. Since Japan does not have enough space to bury this material in landfills, it is necessary to reuse IBA. However, since bottom ash includes toxic material, immobilization is needed for effective use. This study is focused on carbonating treatments that immobilize bottom ash by exhaust gas (EG) and carbon dioxide (CO_2) generated from the Saga city incineration plant. In this incineration plant, CO_2 is separated and collected from EG generated when garbage is incinerated; this is Japan's first carbon dioxide capture and utilization (CCU) plant at a waste incineration facility. The mechanical characteristics and leaching properties of carbonated IBA for use as construction materials, such as base course or embankment materials are determined in tis study using the California bearing ratio (CBR) test, cone index, and leaching tests. As a result, it was revealed that carbonated IBA can be reused as a subbase course material. Also, the leaching concentrations of heavy metals from carbonated IBA were influenced by carbonating treatment processing and its immobilization effect was higher in CO_2 than in EG. It was also revealed that the concentration of lead meets the environmental quality standard values for soils set by the Japanese Ministry of the Environment.

Keywords: incineration bottom ash, carbonating treatment, California bearing ratio, leaching

1 INTRODUCTION

Approximately 1.3 billion tons of municipal solid waste (MSW) was generated globally in 2012. The generation of waste is expected to double by 2025 due to the increase in world population, rate of urbanization, and economic development, which lead to higher consumption of resources (Qadeer Alam et al., 2019). In Japan, approximately 4 million tons of incineration bottom ash (IBA) is discharged per year. IBA from MSW has to be landfilled at the final disposal site to protect the environment. There is a serious capacity shortage at final disposal sites because of limited space. Therefore, alternative uses of IBA, especially as a construction material, are being sought.

The material characteristics of IBA generated from MSW vary due to regional characteristics (e.g., type of waste, volume, place, and season). Even though the mechanical and geotechnical characteristics of IBA have been explored by many researchers, there are a limited number of studies considering the changing trends of IBA components based on its decomposition over time. Under such circumstances, Shariatmadari et al. (2014) experimentally clarified the cohesion and internal friction angle of IBA and accumulated data for more than 20 years. Also, Tony et al. (2008) reported on the cohesion and internal friction angle of IBA for 11 years by means of triaxial compression test results. Moreover, since IBA contains toxic heavy metals, it is necessary to understand not only geotechnical characteristics but also leaching properties to use it as a ground geo-material. David Dabo et al. (2009) reported the ten years chemical evolution of leachate and MSW IBA used in a test road site. However, the effect of aging on not only shear strength of IBA but also leaching properties of IBA has been limited and further studies are needed on the effects of long-term aging to promote effective utilization. Regarding the immobilization of metals in IBA by natural precipitation, Jiang et al. (2009), Kuo et al. (2013), and Augutine Quek et al. (2016) revealed the effectiveness of washing IBA before utilization and that it is necessary not only to reduce heavy metal content, but also to improve mechanical properties. Also, regarding the immobilization of metals in IBA by carbonation and/or weathering, Brenne and Weigand

(2015) show that the aging of bottom ash can be accelerated by enhanced carbonation. Moreover, Kubota et al. (2018) examined the effect of long-term of leaching of IBA by means of on-site bottom ash stabilization treatment that combined water washing and CO_2. Fujikawa et al. (2018) revealed the possibility of effective utilizing IBA by means of an aging method in the landfill. In addition, geotechnical reuse of carbonated material may even lead to revenue when conventional construction materials are substituted by stabilized bottom ash.

Based on the abovementioned background information, this study is focused on a carbonating treatment that immobilizes bottom ash using exhaust gas (EG) and recovered carbon dioxide (CO_2) generated from the Saga city incineration plant in Japan. In this incineration plant, equipment is available to separate and collect CO_2 from EG generated when garbage is incinerated. This is Japan's first carbon dioxide capture and utilization (CCU) plant at a waste incineration facility. In this study, we examined a carbonating treatment that immobilizes IBA by means of two types of carbon dioxide from the CCU plant. This paper describes (1) the bearing capacity of IBA from MSW obtained by the California bearing ratio (CBR) test to investigate the possibility of usage of IBA as a base course material, (2) the mechanical characteristics of the IBA, using the cone index test, to investigate the possibility of usage as an embankment material, and (3) the leaching properties of the IBA from MSW, obtained by the single batch leaching test (Notifications No. 46 Japanese Ministry of the Environment), to evaluate the effect of the carbonating treatments.

2 TESTING PROCEDURE

2.1 Carbonating treatment

According to the Saga city official homepage (2020), in the Saga cleaning plant (garbage incineration facilities), their facility for separation and recovery of carbon dioxide (CO_2 only) from exhaust gas generated during incineration is Japan's first CCU plant in a waste incineration facility. Carbon dioxide (CO_2), which has been said to be the cause of global warming, can actually help foster the promotion of raw materials of carbonated beverages and dry ice and help vegetables and micro-algae grow as a photosynthesis resource. In Saga, to take advantage of carbon dioxide uses in vegetable and algae culture, the plant was allowed to operate the carbon dioxide separation and recovery facilities from August 2016. In this study, we focused on EG and CO_2 and examined a carbonating treatment for immobilizing IBA. Moreover, the effects of the difference between these two types of gases on geotechnical characteristics, such as mechanical properties and leaching, of IBA were investigated. Figure 1 shows the facility flow and gas sampling locations.

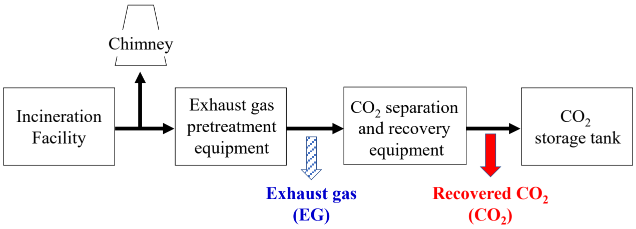
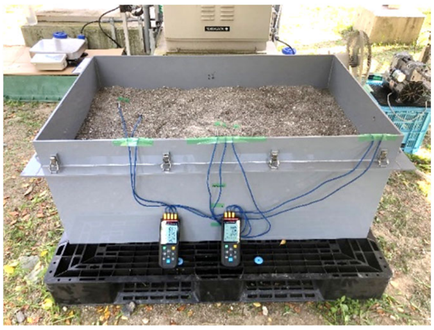
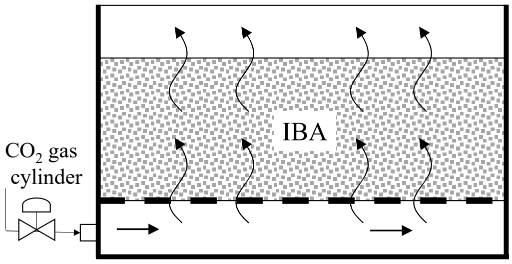


Fig. 1. Facility flow and gas sampling locations.



(a) Photograph of the experimental equipment container



Container size: 1,200 × 750 × 400 mm

(b) Schematic of the experimental equipment container

Fig. 2. Experimental equipment container.

2.2 Materials

The IBA discharged from the Saga incineration facility was used as the experimental samples. This type of IBA at this facility is dry ash discharged from a stoker-type furnace. Therefore, to promote reaction with CO_2, IBA that was previously mixed with water to have a moisture content of 15% was used in the experiment. The reason for setting the IBA water content to 15% here is based on a previous study (Kubota et al., 2020). After the mixed IBA was packed loosely (less than ρ_t = 1.0 g/cm^3) in the container shown in Figure 2 (a), two types of gases were ventilated. The lower part of the container has a hollow structure and pumped gas passes through the IBA and is discharged to the upper part. The carbonated IBA are defined as EG-IBA and CO_2 -IBA. The processing conditions for each gas are shown in Table 1. Since EG and CO_2 have different carbon dioxide concentrations, the total CO_2 amount is set in each condition by adjusting the ventilation speed and ventilation time. As a comparative sample, IBA without carbonating treatment was also used. The physical

Table 1. Processing conditions for EG and CO_2.

Type of gas	CO_2 Concentration (%)	Ventilation speed (L/min)	Ventilation time (h)	Amount of IBA (kgDW)	Packing density (g/cm^3)	Amount of CO_2 (g/kgDW)
EG	7	85	19	138	0.7	90
CO_2	100	38	6.5	293	0.86	93

Table 2. Physical properties of carbonated IBA.

Sample	ρ_s (g/cm^3)	C_u	C_c	F_c (%)
Untreated	2.385	24.7	3.0	11.7
EG-IBA	2.368	49.2	4.4	14.7
CO_2-IBA	2.360	28.5	3.4	14.9

Note: ρ_s = particle density,
C_u = Coefficient of Uniformity, C_c = Coefficient of Curvature,
F_c = concent rate of fine grain fraction

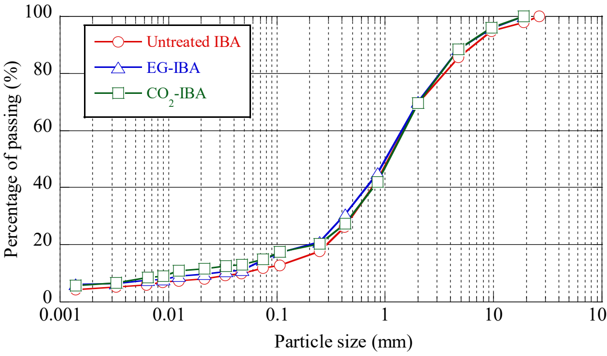


Fig. 3. Grain size distribution curves of IBA materials.

properties of these IBA are shown in Table 2 and the grain size distribution curve is shown in Figure 3. Fine contents (F_c) is slightly increased with the carbonation treatment.

2.3 Experimental details of (California bearing ratio (CBR) test and cone index test

CBR tests (JIS A 1211) were carried out to investigate the possibility of usage of carbonated IBA as a base course material. The CBR index provides a measurement of the impact resistance of compacted carbonated IBA by the E-b method (using 4.5 kg rammer and drying method with non-repeating sample). Table 3 shows the testing conditions of CBR test. The water content of carbonated IBA was adjusted to the optimum water content considering compaction test results. Also, cone index tests (a test method for the cone index of compacted soils, JIS A 1228) were carried out to investigate the possibility of usage of carbonated IBA by the E-b method as an embankment material. Cone indices are typically used to measure soil strength and to identify compacted soil conditions (J.W. Hummel et al., 2004). Table 4 shows the testing conditions of the cone index test. The water content of carbonated IBA was adjusted to the optimum water content considering compaction test results from the CBR test.

Table 3. Testing conditions for the CBR test (JIS A 1211).

Sample	Water content (%)	Compaction Mthod	Weight of Rammer (kg)	Number of Layers	Number of blows	Maximum grain size (mm)
Untreated	Optimum water content	E-b	4.5	3	17	19
EG-IBA					42	
CO_2-IBA					92	

Table 4. Testing conditions for the cone index test (JIS A 1228).

Sample	Water content (%)	Compaction Mthod	Weight of Rammer (kg)	Number of Layers	Number of blows	Maximum grain size (mm)
Untreated	Optimum water content	A-a	2.5	3	25	4.75
EG-IBA						
CO_2-IBA						

Table 5. Testing conditions for the batch leaching test (JLT 46).

Sample	Eluent pH	Liquid-solid ratio (L/S)	Maximum grain size (mm)	Shaking time (hour)	Measurement of heavy metals and metalloid
Untreated	5.8 - 6.3	10	2	6	Pb, Cd, Cr(VI), B, F
EG-IBA					
CO_2-IBA					

2.4 Experimental details and testing conditions of the batch leaching test

It is important to understand the leaching properties of heavy metals in the carbonated IBA. The Japanese Leaching Test No. 46 (Notifications No. 46 by the Japanese Ministry of the Environment, JLT 46) was used to measure concentrations of heavy metals in the carbonated IBA. Table 5 shows the testing conditions of JLT 46. The samples are sieved to less than 2 mm and a solvent is added so that the liquid-solid ratio (L/S) is 10. Inductively coupled plasma atomic emission spectrometry (ICP-AES) was used for analysis of lead (Pb), cadmium (Cd), boron (B), and fluorine (F). For the analysis of hexavalent chromium (Cr (VI)), a spectrophotometer (UVmini-1240) was used by means of diphenylcarbazide absorptiometry. The detection limits of Pb, Cd, B, F and Cr (VI) are 0.01 mg/L, 0.001 mg/L, 0.01 mg/L, 0.08 mg/L, and is 0.02 mg/L, respectively. The reasons for focusing on these heavy metals are that they are included in the Japanese environmental standard values for soils and are in coal ash.

3 RESULTS AND DISCUSSION

3.1 Mechanical characteristics of carbonated IBA as base course material

Figure 4 shows compaction curve relationships between the dry density of each carbonated IBA and water contents obtained from compaction test using the E-b method. The IBA used in this study has a clear peak under each condition. These data indicate that the carbonation treatment slightly reduces the maximum dry density and increases the optimum water content by approximately 5%. Figure 5 shows the results of a CBR test performed using the maximum dry density and the optimum water content obtained by the compaction test results. The CBR index provides a measurement of the impact resistance of the compacted aggregate. It is determined as the ratio between the impact load causing a given penetration in the samples and a fixed pattern (Forteza et al., 2004). Focusing on the untreated results, the IBA satisfied the criteria for base course material (more than 80%: Japanese Geotechnical Society, 2010) regardless of the compaction degree. Regarding the conditions using EG and CO_2, the results satisfied the quality standard of sub base course material (more than 30%: Japanese Geotechnical Society, 2010) regardless of the degree of compaction. These CBR test results indicate that the carbonation treatment tends to lower the CBR value of IBA. The decrease in the CBR value is attributed to the change in unreacted CaO and $Ca(OH)_2$ to $CaCO_3$ due to carbonation and the reduction of compaction force. Fujikawa et al. (2018) showed that each CBR value decrease with increasing carbonation is considered to change the grain size distribution curve of IBA and is also caused by decreased cohesion of IBA. Similarly, Tony et al. (2008) showed the same result as Fujikawa et al. (2018) with respect to a decrease in adhesive strength with an increase in the duration of aging.

From our results it is revealed that the IBA can be effectively used as sub base course material based on its mechanical properties, even though the CBR value decreased due to carbonation.

3.2 Mechanical characteristics of carbonated IBA as embankment material

Figure 6 shows compaction curve relationships between the dry density of each carbonated IBA and water contents obtained from compaction tests using the A-a method (using 2.5 kg rammer and drying method with repeating sample). Although there was no change in the maximum dry density, it was found that the optimum water content tended to increase by 5% by the carbonation treatment as in the CBR test results. Figure 7 shows the results of a cone index test performed using the maximum dry density and the optimum water content obtained by the compaction test results. As in the case of

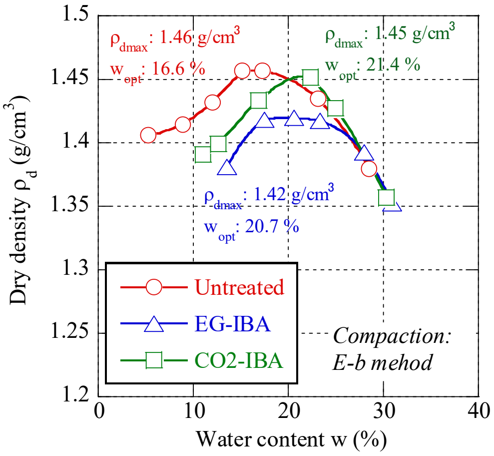


Fig. 4. Compaction curve relationships between dry density of each carbonated IBA and water contents.

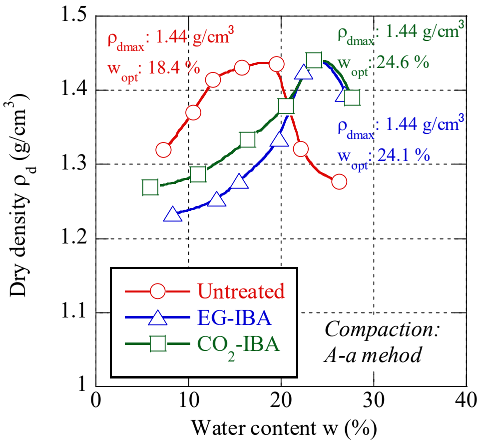


Fig. 6. Compaction curve relationships between the dry density of each carbonated IBA and water content.

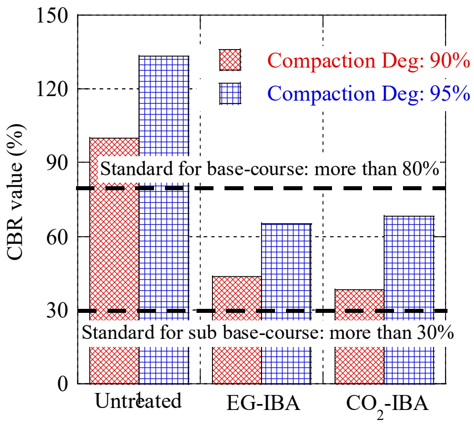


Fig. 5. Results of CBR test performed using the maximum dry density and the optimum water content.

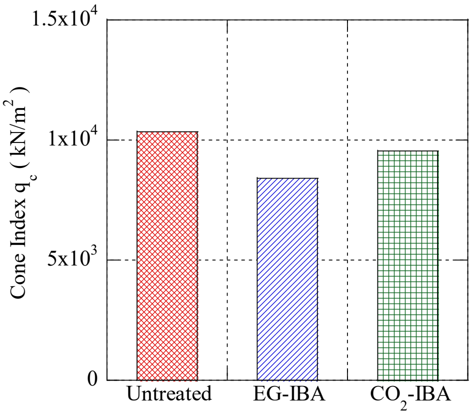


Fig. 7. Results of cone index tests performed using the maximum dry density and the optimum water content.

the CBR test results, the cone index is slightly reduced by carbonation. Generally, the unconfined compressive strength (UCS) required for embankment material is $q_u = 100\text{-}300$ kN/m^2. Considering that the cone index is equivalent to about five times the uniaxial compressive strength, as shown in equation (1).

$$q_u \cong \frac{1}{5} \cdot q_c \tag{1}$$

where q_u is unconfined compressive strength (kN/m^2) and q_c is cone index (kN/m^2) (Japan Cement Association, 2014), in the EG-IBA showing the lowest cone index value the converted UCS is approximately 1,700 kN/m^2.

Based on the above results, it was clarified that IBA could be used as embankment material regardless of the presence or absence of carbonation.

3.3 Leaching properties and environmental safety assessment of carbonated IBA

Table 6 shows the batch leaching test results (JLT 46). Focusing on Pb, even though untreated IBA has a high concentration of elution, the concentration of the elution of carbonated IBA by means of EG and/or CO_2 is suppressed to below the soil environmental standard value set by the Ministry of the Environment in Japan. In addition, it was revealed that even though carbon dioxide concentration, ventilation speed, and ventilation time were adjusted so that the total amount of carbon dioxide gas to be passed was equal, the immobilizing effect was particularly high in CO_2 compared with EG. This is because CO_2 has a higher gas concentration and a slower aeration rate than EG, therefore the reaction was spread slowly throughout. The elution of B in the CO_2 condition is attributed to a decrease in pH value.

Regarding other heavy metals and metalloids except Cr (VI), all satisfied the soil environmental standards regardless of the difference in carbonation treatment. However, the carbonation of Cr (VI) exceeded the soil environmental standard value. The reason why the concentration of Cr increased was attributed to shift of the oxidation-reduction potential of Cr (III) in IBA to the acidic side, changing it into Cr (VI). Alternatively, it is possible that Cr (VI) was present in IBA from the beginning (fixed to a hydrate), etc.) and that hydrate was destroyed by carbonation to release Cr (VI). Regarding this point, it is necessary to correctly quantify and confirm the initial content of hexavalent chromium and the content after carbonation. Therefore, further studies to suppress the elution of Cr (VI) due to carbonation are necessary.

Table 6. Batch leaching test results (JLT 46).

Sample	pH	Pb (mg/l)	Cd (mg/l)	Cr(VI) (mg/l)	B (mg/l)	F (mg/l)
Untreated	12.78	4.7	N.D.	0.04	N.D.	0.35
EG-IBA	11.92	0.02	N.D.	0.19	0.19	0.18
CO_2-IBA	10.94	N.D.	N.D.	0.15	0.93	0.29
Soil environmental standard values set by the Ministry of the Environment in Japan		< 0.01	< 0.003	< 0.05	< 1	< 0.8
Lower limit of quantification in this experiment		0.01	0.001	0.02	0.01	0.08

4 CONCLUSIONS

In this study, we examined the applicability of IBA, using two types of carbonation treatment, as construction materials, such as base course and embankment materials, and its environmental safety.

Even though the carbonation treatment tends to lower the CBR value of IBA, carbonated IBA can be effectively used as a sub base course material based on its mechanical properties and regardless of the carbonation conditions. Also, carbonated IBA can be effectively used as embankment material since it has a sufficient cone index value. Regarding heavy metal and metalloid leaching behavior, it was revealed that all IBA samples satisfied the soil environmental standards value set by the Ministry of the Environment in Japan, except for Cr (VI). The immobilizing effect was particularly high for Pb in CO_2 compared with EG. However, the carbonation of Cr (VI) exceeded the soil environmental standard value. Therefore, it is necessary to take measures to immobilize Cr (VI) in future studies.

ACKNOWLEDGMENTS

This research was supported by the Environment Research and Technology Development Fund (3-1804) of the Environmental Restoration and Conservation Agency of Japan. Also, this research was supported by Saga city by helping to carry out the experiment.

REFERENCES

1) Augustine Quek, Wenyu Xu, Lin Guo and Dongqing Wu (2016): Heavy Metal removal from Incineration Bottom Ash through Washing with Rainwater and Seawater, *International Journal of Waste Resources*, Vol.6, Issue 1, 1000203.
2) T. Brenne and H. Weigand (2015): Stabilization of heavy metals in MSWI bottom ash by dynamic carbonation, *Proceedings of the 14th International Conference on Environmental Science and Technology*, CEST2005_00227.
3) David Dabo, Rabia Badreddine, Laurent De Windt, Ivan Drouadaine (2009): Ten-year chemical evolution of leachate and municipal solid waste incineration bottom ash used in a test road site, *Journal of Hazardous Materials* 172, 901-913.
4) Hiroshi Kubota, Koga Shigeizumi, Takuro Fujikawa, Chikashi Koga, kenichi Sato (2018): An accelerated, on-site bottom ash stabilization treatment and the effect of long-term leaching of bottom ash, *10th International Conference on the Environmental and Technical Implications of Construction with Alternative Materials*, 229-235.
5) Japan Cement Association (2014): Ground Improvement Manual with cement solidification material, p.94. (in

Japanese)

6) Japanse Geotechnical Society (2010): Basic and Companion of Soil test, *Doshitsusiken Kihon to Tebiki.*, p89. (in Japanese)
7) Yonghai Jiang, Beidou Xi, Xiujin Li, Ling Zhang, Zimin Wei (2009): Effect of water-extraction on characteristics of melting and solidification of fly ash from municipal solid waste incinerator, *Journal of Hazardous Materials* 161, 871-877.
8) JIS (2009) A 1211: ThemMethod for the California Bearing Ratio (CBR) of soils in laboratory. Japan Industrial Standard, Japanese Industrial Standards Committee, Tokyo, Japan.
9) J.W. Hummel, I.S. Ahmad, S.C. Newman, K.A. Sudduth, S.T. Drummond (2004) *Simulations Soil Moisture and Con Index Measurement, Transactions of the ASAE*, Vol. 47(3), 607-618.
10) Hiroshi Kubota, Koga Shigeizumi, Takuro Fujikawa, Chikashi Koga and Kenichi Sato (2020): An accelerated, On-Site Bottom Ash Aging and Washing Treatment and Its Effect for Long-Term Leaching, *Waste and Biomass Valorization*, Vol.11, 7067-7077.
11) N. Shariatmadari, A. H. Sadeghpour, and F. Razaghian (2014): Effects of aging on shear strength behavior of municipal solid waste, *International Journal of Civil Engineering*, 226-237.
12) Qadeer Alam, Katrin Schollbach, Marco Rijnders, Corrie van Hoek, Sieger van der Laan, H.J.H. Brouwers (2019): The immobilization of potentially toxic elements due to incineration and weathering of bottom ash fines, *Journal of Hazardous Materials* 379, 120798.
13) R. Foreza, M, Far, C. Segui, V. Cerda (2004): Characterization of bottom ash in municipal solid waste incinerators for its use in road base, *Waste Management* 24, 809-909.
14) Saga city official homepage (2020): For carbon dioxide separation and recovery equipment (Accessed on 6th Mar. 2020). https://www.city.saga.lg.jp/main/44494.html
15) Takuro Fujikawa, Kenichi Sato, Chikashi Koga, and Hirofumi Sakanakura (2018): Evaluation of Environmental Safety on Municipal Solid Waste Incineration Bottom Ash Using Aging Method, *Proceedings of the 8th International Congress on Environmental Geotechnics*, vol.1, 320-327.
16) Tony L.T. Zhan, Y.M. Chen, W.A. Ling (2008): Shear strength characterization of municipal solid waste at the Suzhou landfill, China, *Engineering Geology* 97, 97–111.