Original Paper

Effect of Accelerated Carbonation on the Mineral Phase of Alkaline Inorganic Waste

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Abstract

To effectively pre-treat the alkaline inorganic waste by carbonation reaction with CO₂, it is necessary to understand a mineralogical change. This is because mineralogical changes serve as an important key to leaching behavior or stabilization of heavy metals, such as Pb, Cu, Cr, and Ni, contained in the inorganic waste, at the point of environmental influence. Therefore, in this study we investigated the chemical composition and mineralogical characteristics of municipal solid waste incineration bottom ash, which is a type of alkaline inorganic waste, and the material changed by the carbonation reaction in bottom ash. In addition, minerals affected by carbonation reactions were identified based on the ternary diagram of Ca-Al-Si in bottom ash. The relationship between mineralogical changes caused by carbonation reactions and stabilization of heavy metals was also examined.

Key words: Alkaline inorganic waste, MSWI bottom ash, Carbonation reaction, Ternary diagram of Ca-Al-Si

1. Introduction

In South Korea, the industries of many fields have generated massive amounts of inorganic waste such as municipal waste incinerator bottom ash, municipal waste incinerator fly ash, steel slag, power plant bottom ash, waste concrete, and waste lime¹. Most inorganic waste is buried in designated burial sites, resulting in a low recycling rate. While efforts are being made to utilize old burial sites as sports complexes or golf clubs, this is not a fundamental solution to the problem because it is difficult to acquire more sites from the limited land in Korea². Thus, there is a need to facilitate waste management by increasing the recycling ratio instead of burying waste.

Carbonation processing technology with CO₂ for effective pre-treatment of the inorganic waste has come under the spotlight as a means of

waste-resource recovery and is being developed for the stabilization of hazardous substances. In addition, the sequestration of CO₂ into inorganic waste, along with geologic storage, offers storage of high amounts of CO₂, and the research on CO₂-based waste processing can be a solution to the challenge of reducing greenhouse gases amid the accelerated pace of global warming^{3,4}.

In general, for applying carbonation technology to inorganic waste, the below conditions were used to separate the respective alkaline inorganic waste⁵:

- Waste exists in solid form
- Waste is fully inorganic
- Waste is in an alkaline state (pH > 8)
- Waste contains non-carbonated Ca and Al compounds

Alkaline inorganic waste satisfying the above conditions easily engages in reactions with CO₂. Using carbonation reactions to pre-treat inorganic waste has the effect of neutralizing the alkaline state, decomposition of insoluble chlorides, and stabilizing heavy metals. In order to understand

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these effects, it is essential to study mineralogical changes of alkaline inorganic waste^{6,7}. Some important factors may be chemical composition and mineralogical characteristics of alkaline inorganic waste, material changes by carbonation reaction, and consequences on the environment. Therefore, in this study, the mineralogical characteristics and mineralogical changes caused by carbonation reaction with a focus on municipal waste incinerator bottom ash that is a type of alkaline inorganic waste. In addition, the material affected by carbonation reaction was identified based on the ternary diagram of Ca-Al-Si in bottom ash and the effect of heavy metals stabilization was also studied.

2. Material and Methods

2.1 Material

Samples of municipal waste incinerator bottom ash were obtained from an incinerator plant in Gwangmyeong-city in Gyeonggi province, Korea. In this incinerator plant, municipal waste was incinerated at a temperature of 1000°C, and the moisture content of bottom ash was 30 w/w.% as it is cooled by water-cooling after incineration. For particle separation, the moisture content of the bottom ash was kept below 1% by drying for 24 hours in an oven of 105°C. For removal of large iron fraction, a magnetic separator with a magnetic strength of 0.38 T was used. After magnetic separation, the bottom ash was passed through a standard sieve to obtain particles larger than 4.75 mm, 4.75–2.36 mm, 2.36–1.18 mm, 1.18–0.6 mm, 0.6–0.3 mm, 0.3–0.15 mm, 0.15–0.075 mm and smaller than 0.075 mm. An X-ray fluorescence spectrometer (Rigak TXRF 3726AI, Rigaku) was used to derive chemical compositions of bottom ash in each particle size. Fig. 1 shows the chemical composition of only Ca, Si, and Al in each particle size because of the most abundant in bottom ash. The concentration of Si increased with an increase in the particle size owing to the increased amounts of glass and synthetic ceramics, whereas Ca and Al increased with a decrease in the particle size.

2.2 Leaching test

A leaching test (standard method of the Korean Standard Leaching Procedure) was performed to measure the leached amount of Cr and Cl and the pH before and after carbonation. The bottom ash and diluted water were in the ratio of 1:10 (Solid/Liquid, w/w.%), and HCl was added to adjust the pH to 5.8–6.3. After stirring for 6 hours at 200 rpm, solid and liquid were separated by a fil-

Fig. 1 Ca, Al, and Si contents in the bottom ash as a particle size.

ter paper with a pore size of 0.5 μm . The concentration of Cr and Cl and pH in the leachate were measured using an inductively coupled plasma atomic emission spectrometry (OPTIMA 5300DV, Perkin Elmer) and a pH electrode (SN5135011).

2.3 Carbonation reaction

To confirm the mineralogical change of the bottom ash before and after carbonation in terms of the three phases of Ca-Si-Al, samples were prepared for carbonation reactions by selecting particles with a relatively small grain size of 0.6–0.3 mm and because of well distribution of the three phases, as shown in Fig. 1. Cylindrical-type samples were created by mixing polymers and bottom ash, and then cut to reveal cross-sections. 105 particles on the surface of cross-sectional areas of samples were selected and numbered as shown in Fig. 2. Using the SEM and EDX (JSM-6400) equipment, compositional analysis was conducted to analyze the surface of cross-sectional areas. EDX was used for compositional analysis of the subjects with main elements (Ca, Si, Al), heavy metal elements (Fe, Cu, Cr, Pb), and other elements (Na, K, Cl, etc). Next, the samples were sandpapered to remove the Au coating on the surface of cross-sections. The carbonation experiments were performed in a CO₂ incubation chamber to keep the CO₂ percentage at 30% and the temperature at 25°C during 4 hrs carbonation time, as shown in Fig. 3. The humidity of the reactor was maintained at 50%. After carbonation reaction, mineralogical changes of 105 particles on the surface of cross-sections area were also observed using SEM.

Fig. 2 Mapping of sample showing the section of bottom ash particles.

Fig. 3 Pictures of samples and carbonation equipment.

3. Results and Discussion

3.1 Chemical composition and mineralogical characteristics of alkaline inorganic waste

Many references⁸⁻¹¹ with an analysis of mineral phases of municipal solid waste incinerator bottom ash explain that the bottom ash consists mostly of quartz, calcite, magnetite, hematite, gypsum, ettringite, akermanite, gehlenite, and cristobalite. These crystalline compounds are comprised of Ca, Al, and Si, and traces of Fe, Na, Mg, Cl, and so on. The bottom ash is more than 40% glassy with particles of the vesicular, porous, coke, or crack type. The morphological characteristics of particles in bottom ash are closely related to exposure in air, contact with water, and the various type of cooling process after incineration, and these factors will form new substances by react-

ing with those still remaining after incineration. The new substances are largely divided into silicate-type glassy substances and irregular or aggregate-type Ca-Al compounds. In the point of view of the relationship between new substances and carbonation method with CO₂, it is important to determine the conditions for carbonation reactions by confirming the chemical composition and mineral phase of each particle, and identifying minerals capable of easily reacting with CO₂. Therefore, the cross-sectional areas of particles were observed for mineralogical characteristics, particle types, and whether or not carbonation has occurred. The measurements obtained are organized in Table 1. Fig. 4 is a graphical representation for Ca-Al-Si content ratio of 105 particles with main Ca, Al, and Si compounds.

As shown in Table 1, particle types are described as vesicular, silicate, porous, aggregate, whisker, coke, anisotropic, irregular, and crack. Silica-type minerals including silicate existed as aggregate and irregular types, and various forms of minerals of Ca and Al, such as vesicular, porous, coke, and crack, were observed on the surface. To confirm the overall mineralogical characteristics of bottom ash, 105 particles were represented based on the ternary diagram of Ca-Al-Si, as shown in Fig. 4. As seen in ternary diagram, there were hardly any minerals with a high proportion of Al due to the low Al content. Metal substances (Fe, Cu, Al, and Cr) and other elements (Na, Mg, K, and Cl) were also detected in each particle as the form of metal fragments or metal compounds, while Na and K were soluble chlorides. Cl existed as soluble chlorides together with Na and K, or as insoluble Friedel's salt with Ca¹².

More than 40% of bottom ash was minerals with high amounts of Si. They mostly exist as SiO₂ or as a silicate-type compounds and these particles agglomerate with Ca-Al compound to form large clusters. As for Ca, it can be found as calcium carbonate, or as Friedel's salt and ettringite with Al. The high pH in bottom ash is caused by these Ca-Al compounds and traces of CaOH. Fig. 5 gives the main minerals with Ca-Al-Si in bottom ash. Fig. 5(a) is the typical SiO₂ (silica) and silicate, Fig. 5(b) shows Ca-Al compounds attached to silicate, and Fig. 5(c) and Fig. 5(d) represent calcium carbonate and CaOH₂ respectively. Fig. 6, the same as Fig. 5(b), is the SEM and EDX analysis for Ca-Al compounds attached around silicate-type particles. These aggregate particles are most commonly seen in Ca-Al-Si minerals with various porous structures of the

Table 1 Content ratio of Ca-Al-Si, particle type, and carbonation reaction on the surface of bottom ash sample (including 105 particles)

No.	carbonation	Ca (%)	Al (%)	Si (%)	Particle type	Note
1	Not	100	0	0	Vesicular	CaCO ₃
2	Not	8	25	67	Silicate	
3	Not	0	0	100	Vesicular	SiO ₂
4	Not	27	27	46	Large porous	Na, Mg contained
5	Yes	73	27	0	Aggregate	Cl, Mg contained
6	Not	11	27	62	Silicate	
7	Not	19	6	75	Silicate	
8	Not	—	—	—	Whisker	Fe-metal
9	Not	75	25	0	Coke	
10	Not	—	—	—	Elliptic	Fe-metal and Fe-oxide
11	Partial	28	29	43	Vesicular	
12	Not	8	23	69	Silicate	
13	Not	10	25	65	Silicate	
14	Yes	—	—	—	Aggregate	Na-Zn compound
15	Not	20	20	60	Large porous	
16	Not	4	13	83	Silicate	
17	Not	74	9	17	Anisotropic	Ca-Zn compound
18	Not	72	11	17	Aggregate and porous	
19	Not	43	19	38	Aggregate	
20	Not	42	33	25	Aggregate and porous	
21	Not	20	13	67	Aggregate and porous	
22	Not	8	34	58	Elliptic	
23	Not	7	22	71	Vesicular	
24	Not	12	19	69	Aggregate and porous	
25	Yes	92	6	2	Aggregate	Na, Cl, Mg contained
26	Not	45	55	0	Irregular	
27	Not	42	33	25	porous	
28	Not	7	13	80	Silicate	Na contained
29	Not	6	12	82	Silicate	Na contained
30	Yes	50	50	0	Irregular	Cl contained
31	Not	0	0	100	Vesicular	SiO ₂
32	Partial	30	20	50	Aggregate and crack	
33	Partial	42	25	33	Large porous	Cl, Cr, Fe contained
34	Partial	24	19	57	Aggregate	
35	Partial	22	17	61	Aggregate	Na contained
36	Not	20	7	73	Silicate	Na contained
37	Not	26	33	40	Large porous	
38	Not	15	8	77	Silicate	Na contained
39	Not	9	8	83	Silicate	Na contained
40	Not	27	6	67	Silicate and porous	Na contained
41	Not	21	36	43	Crack and porous	
42	Not	16	18	66	Silicate and porous	
43	Yes	82	6	12	Irregular	
44	Not	22	8	70	Silicate and large porous	
45	Not	54	18	28	Aggregate and large porous	Fe-iron contained
46	Not	13	47	40	Aggregate and large porous	
47	Not	0	47	53	Irregular and porous	
48	Not	55	27	18	Aggregate and crack	Fe-iron contained
49	Not	98	1	1	Irregular and porous	CaCO ₃
50	Not	33	44	23	Irregular and porous	
51	Not	97	3	0	Vesicular	CaCO ₃ containing Cl
52	Not	27	18	55	Large porous	
53	Not	9	3	88	Silicate	Na contained
54	Partial	16	28	56	Irregular and large porous	Fe, Na contained
55	Not	0	35	65	Silicate	Na contained
56	Partial	45	27	28	Aggregate and porous	
57	Not	80	16	4	Aggregate and porous	
58	Not	0	0	100	Silicate	

Table 1 (continued)

No.	carbonation	Ca (%)	Al (%)	Si (%)	Particle type	Note
59	Not	17	16	67	Aggregate and large porous	Mg, Na contained
60	Not	59	12	29	Aggregate and porous	
61	Not	24	9	67	Aggregate and large porous	Na contained
62	Not	0	0	100	Silicate	
63	Not	32	10	58	Aggregate and large porous	Na, Mg contained
64	Not	10	4	86	Silicate and crack	Na contained
65	Not	28	0	72	Aggregate	
66	Not	57	29	14	Vesicular	
67	Not	43	21	36	Irregular	Fe-oxide contained
68	Not	—	—	—	Vesicular	Na and Mg compound containing Fe-oxide
69	Partial	14	7	79	Aggregate and porous	
70	Partial	36	21	43	Aggregate and large porous	Fe-oxide contained
71	Not	50	25	25	Vesicular	
72	Not	24	6	70	Aggregate	
73	Not	95	4	1	Irregular and porous	CaCO ₃
74	Not	33	25	42	Aggregate	
75	Not	39	30	31	Aggregate and porous	
76	Not	24	12	64	Aggregate and porous	
77	Not	35	18	47	Aggregate and large porous	Na, Mg contained
78	Not	0	0	100	Vesicular	SiO ₂
79	Not	94	3	3	Irregular and porous	CaCO ₃
80	Not	32	7	61	Aggregate	
81	Yes	73	12	15	Irregular and crack	
82	Not	19	35	46	Vesicular	
83	Not	39	61	0	Anisotropic	Zn contained
84	Yes	71	14	15	Irregular and crack	
85	Not	99	0	1	anisotropic	Na contained
86	Partial	32	23	45	Aggregate and large porous	
87	Yes	92	5	3	Irregular and porous	Na contained
88	Not	0	0	100	Silicate	
89	Not	34	7	59	Aggregate and large porous	Fe, Na, Cl contained
90	Yes	95	5	0	Irregular and crack	Cl contained
91	Not	46	21	33	Vesicular and large porous	Na, Mg, Cl, K contained
92	Not	10	0	90	Aggregate and large porous	Mg-Si compound
93	Not	96	4	0	Irregular and porous	Ca-P compound
94	Weak	69	24	7	Irregular and porous	Na, Cl contained
95	Not	1	1	98	Silicate	
96	Not	97	0	3	Silicate	K contained
97	Not	0	0	100	Silicate	
98	Weak	60	40	0	Aggregate, porous and crack	Na-Cu mineral contained
99	Weak	77	23	0	Irregular	
100	Not	100	0	0	Irregular and crack	
101	Not	22	17	61	Aggregate and porous	Fe-iron contained
102	Yes	100	0	0	Irregular and crack	
103	Not	0	100	0	Irregular and porous	Amorphous Al-oxide
104	Yes	59	35	6	Irregular and crack	Na, Mg, Cl, K contained
105	Yes	79	18	3	Irregular and crack	Na, Cl contained
106	Not	5	22	73	Vesicular	Mg, Cl, Mg contained
107	Yes	70	27	3	Irregular and crack	Na, Cl, K contained
108	Not	40	25	35	Aggregate and porous	Mg contained
109	Not	28	11	61	Irregular and large porous	Na contained
110	Not	0	0	100	Silicate	
111	Partial	30	32	38	Aggregate	Na, Mg, Cl, K contained
112	Not	30	13	57	Aggregate and large porous	Na, Mg contained
113	Not	0	0	100	Silicate	
114	Not	98	1	1	Irregular and porous	
115	Not	13	19	68	Vesicular and crack	Na, K contained

Fig. 4 Diagram of Ca, Al, and Si content ratio in each bottom ash particle.

Fig. 6 SEM and EDS analysis of silicate surrounded with Ca-Al compound.

Fig. 5 SEM analysis of main minerals with Ca-Al-Si in bottom ash; (a) typical silica (SiO_2) and silicate, (b) Ca-Al compounds attached to silicate, (c) calcium carbonate, and (d) $\text{Ca}(\text{OH})_2$.

Fig. 7 SEM analysis of constituents with heavy metals; (a) Fe-metal and Cu-metal existing as a whisker-type, (b) Fe-oxide intertwined with vitreous materials, (c) Al-metal agglomerating with other compounds, (d) Cr-metal existing in the inner porous layer of Ca-Al compounds.

bottom ashes generated from incinerator after incineration process.

Next, the characteristics of metal substances in bottom ash were confirmed. Fe-material, which has the highest distribution among metals, accounted for more than 10% of bottom ash. Most Fe was Fe-metal and Fe-oxide that was formed by oxidation from the corrosion of Fe-iron. The majority of Fe-metal coated with Fe-oxide existed independently, whereas some Fe-oxide was aggregated with other particles and difficult to separate by magnetic separation¹³. Fig. 7(a) and Fig. 7(b) show that Fe-metal and Fe-oxide intertwined with vitreous materials. As shown in Fig. 7(c), the picture shows Al-metal agglomerating with other compounds. This picture may be evidence about the low separation ratio using an

eddy current separator as well as the surface oxidized as Al-oxide¹⁴. Thus, more research on Al detection and separation has to be studied, because that cracks are formed if Al-containing bottom ash is reused for buildings or pavements. In Fig. 7(a), we can see Cu-metal existing as a whisker type and being surrounded by vitreous materials. Cr-metal, as presented in Fig. 7(d), was found in the inner porous layer of Ca-Al compounds. The existence of heavy metals in bottom ash particles must be determined in more detail since such metals involve a risk of leaching into solution.

3.2 Effect of accelerated carbonation on the mineral phase

The bottom ash produces unstable Ca-Al compounds during the water-cooling process (cooling down the incinerated high-temperature bottom ash before it goes to the landfill) following incineration. Because these substances contain various metal components, they can play an important role in the leaching of heavy metals, which have an environmental impact. These compounds are generated in alkaline bottom ash, as follows below.

In the case of Ca, it changes to CaO when incinerated at a temperature of 1000°C, and the water cooling process appears to control the formation of portlandite ($\text{Ca}(\text{OH})_2$). In addition, ettringite ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$) and Friedel's salt (or hydrocalumite; $\text{Ca}_2\text{Al}(\text{OH})_6\text{Cl} \cdot 2\text{H}_2\text{O}$) are controlled by the water cooling process, as they are in an environmental condition in which they can be formed. Regarding the formation and properties of ettringite, the stability domain for ettringite generally lies between pH 10.5 and pH 13. Its formation is generally favored over mono-sulfate at low temperatures, below 50°C. In the case of Friedel's salt, it is synthesized in the Ca-Al-Cl system at 65°C and the pH is kept constant at over 11.5 according to the following equation^{15,16}:

Ettringite:

Friedel's salt:

$\text{Ca}(\text{OH})_2$, ettringite, and Friedel's salt are unstable Ca-Al compounds in bottom ash that show distinct changes in carbonation reactions with CO_2 . To explain the characteristics of the variation in the mineral phase of bottom ash via a carbonation reaction, the XRD diffraction of before and after carbonation reaction has to be investigated. The mineral phases of bottom ash obviously changed with carbonation reaction have been reported in the literatures^{11,17,18}. The decomposition of $\text{Ca}(\text{OH})_2$, ettringite, and Friedel's salt from carbonation is as follows^{19,20}.

As shown in chemical reactions, calcite became the main crystalline phase in the carbonated bottom ash upon the decomposition of portlandite, ettringite, and Friedel's salt. These reactions may be interpreted as suggesting the possibility of the formation of a new amorphous product, Al-oxide, which forms due to the dissolution of ettringite and Friedel's salt. As presented in Table 1, each particle in bottom ash was checked for carbonation. Fig. 8 shows the ternary diagram of Ca, Al, and Si content ratio in each particle after carbonation reaction, like Fig. 4. As a result, most minerals that have been subject to carbonation were found to exist as Ca-Al compounds. This result indicates that the aforementioned decomposition reactions of $\text{Ca}(\text{OH})_2$, ettringite, and Friedel's salt are main carbonation reactions in bottom ash. Fig. 9 shows SEM analysis of the surface of particles affected by carbonation reaction. They can be broadly classified into three types. Carbonation reactions can occur either on the entire surface of Ca-Al compounds or on part of the surface of Ca-Al compounds agglomerating with silicate or other materials, and this is believed to be caused by the carbonation reaction of ettringite and Friedel's salt with CO_2 . In addition, the most active reactions took place in $\text{Ca}(\text{OH})_2$, which is illustrated in Fig. 9(c).

3.3 Carbonation effect on heavy metal stabilization

As mentioned above, the three substances with $\text{Ca}(\text{OH})_2$, ettringite, and Friedel's salt are decom-

Fig. 8 Diagram of Ca, Al, and Si content ratio in each bottom ash particle after carbonation reaction.

Fig. 9 SEM analysis of three types of the particles affected by carbonation reaction; (a) occurring on the entire surface of Ca-Al compound, (b) occurring on part of the surface of Ca-Al compound agglomerating with silicate, (c) occurring on the surface of Ca(OH)_2 .

posed after carbonation, producing CaCO_3 and Al_2O_3 . In particular, Al_2O_3 is known as an amorphous material, highly adhesive substance with heavy metal ions. As can be seen from many references^{6,11,21} about the stabilization of heavy metals according to carbonation reaction, the generation of CaCO_3 and amorphous Al_2O_3 has a significant effect on the control of heavy metal's leaching. Fig. 10 is the SEM image showing mineral changes caused by carbonation reaction on the surface of particles containing Cr-fractions, and can be used as evidence in explaining the effect of carbonation on the stabilization of heavy metal. As seen in Fig. 10, we could confirm that Cr-fractions exist in the inner porous layer of Ca-Al compounds before carbonation reaction, but new and irregularly-shaped substances with CaCO_3 and amorphous Al_2O_3 are wrapped around Cr-fractions after carbonation reaction. This provides evidence of the morphological changes in the particles in what is termed the encapsulation effect^{21,22}.

Fig. 10 SEM analysis of Ca-Al compound with Cr-material (a) before and (b) after carbonation reaction.

Table 2 Leaching concentrations of Cr, the removal ratio of Cl, and pH changes caused by carbonation reaction

	Leaching concentration of Cr (mg/L)	Removal ratio of Cl (wt/wt.%)	pH
Before carbonation	0.40	0	12.0
After carbonation	0.01	92.4	8.9

Regarding the confirmation of Cr leaching behavior, Cl and pH, and Cr behaviors during 4 hrs of carbonation reaction time were investigated. Table 2 shows the leaching concentrations of Cr, the removal ratio of Cl, and pH changes caused by carbonation reaction. We can consider the variation of the pH as a function of carbonation time. Before the carbonation reaction, bottom ash is highly alkaline with a pH of 12 due to the presence of ettringite, hydrocalumite, and portlandite, but pH falls when these substances are decomposed during initial carbonation. Eventually, the pH falls below 9 after carbonation reactions, and the value is determined by the newly formed calcite, amorphous Al_2O_3 , and gypsum. The decomposition of ettringite and hydrocalumite from CO_2 reactions also affects the removal ratio of Cl from the bottom ash. As shown in Table 2, the removal ratio of Cl increased during the carbonation reaction. In the case of Cr, it decreased until below 0.1 mg/L. Cr-stabilization is supported by two findings by the carbonation reaction. First, the carbonation reaction is to decrease the pH and to form insoluble Cr-material that contributes to a reduction of the leaching. Secondly, the adsorbent compound, which is amorphous Al-material formed by the carbonation reaction and has high affinity of Cr, in the bottom ash, controls the leaching of Cr. In addition, the encapsulation effect, mentioned in Fig. 10, occurring on the surface of the bottom ash particles results in more effective stabilization of Cr leaching behavior.

4. Conclusions

In this study, the effect of accelerated carbonation on the mineral phase of alkaline inorganic waste was investigated. In order to confirm the carbonation effect, the important factors with the chemical composition and the mineralogical characteristics of alkaline inorganic waste, the accelerated carbonation on the mineral phase were also examined with focus on municipal waste inciner-

ator bottom ash that is a type of alkaline inorganic waste.

In this result, the bottom ash was largely divided into silicate-type glassy material and aggregate-type Ca-Al compounds. After carbonation processing with CO₂, the carbonation reaction in bottom ash could occur on the surface of Ca-Al compounds agglomerating with silicate, other materials, and heavy metals, and this is to be caused by the carbonation reaction of ettringite, Friedel's salt, and Ca(OH)₂ with CO₂.

In addition, we also confirmed the effect of heavy metals stabilization in bottom ash during carbonation reaction, and this result showed that the leaching of Cr, on behalf of heavy metals, started to decrease after carbonation reaction and fell under the initial value of Cr leaching in the untreated bottom ash. Calcium carbonate and amorphous Al-oxide formed by decomposition of Ca(OH)₂, ettringite, and Friedel's salt has a significant influence on the leaching characteristics of Cr. The encapsulation effect, showing the amorphous Al-materials precipitated on the surface of the carbonated bottom ash particles, allowed for more effective stabilization of the leaching behavior of Cr.

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