

## CO<sub>2</sub> sequestration and heavy metal stabilization by carbonation process in bottom ash samples from coal power plant

Ramakrishna. CH<sup>1</sup>, Thriveni. T<sup>2</sup>, Seong Young Nam<sup>3</sup>, Chunsik kim<sup>4</sup> and Ahn Ji Whan<sup>5\*</sup>

<sup>1,2</sup>Hanil Cement, 302 Maepo-gil, Maepo-eup, Danyang-gun, Chungcheongbuk-do, Korea.

<sup>3,4</sup>Technical Center, HANIL CEMENT Co.Ltd. 50, Daehwa-ro 52beonan-gil, Daedeok-gu, Daejeon, 34361, Republic of Korea.

<sup>5</sup>Mineral Processing Division, Korea Institute of Geoscience and Mineral Resources (KIGAM), Gwahagno-124, Yuseong-gu, Daejeon, Korea.

(Received 20 November 2017, Revised 11 December 2017, Accepted 13 December 2017)

### Abstract

Coal-fired power plants supply roughly 50 percent of the nation's electricity but produce a disproportionate share of electric utility-related air pollution. Coal combustion technology can facilitate volume reduction of up to 90%, with the inorganic contaminants being captured in furnace bottom ash and fly ash residues. These disposal coal ash residues are however governed by the potential release of constituent contaminants into the environment. Accelerated carbonation process has been shown to have a potential for improving the chemical stability and leaching behavior of bottom ash residues. The aim of this work was to quantify the volume of CO<sub>2</sub> that could be sequestered with a view to reducing greenhouse gas emissions and stabilize the contaminated heavy metals from bottom ash samples. In this study, we used PC boiler bottom ash, Kanvera reactor (KR) slag and calcined waste lime for measuring chemical analysis and heavy metals leaching tests were performed and also the formation of calcite resulting from accelerated carbonation process was investigated by thermo gravimetric and differential thermal analysis (TG/DTA).

**Key words** : Heavy metals, Carbonation, Coal power plant bottom ash

## 1. INTRODUCTION

Major environmental problems around the world are usually due to the disposal of waste materials such as industrial waste, construction waste, household waste and etc. However, industrial waste, also known as production by-products, has been investigated extensively as sustainable alternatives to Portland cement in concrete [1,2]. Recently, waste accumulation has become a major problem to the environment as well as human beings [3]. Heavy metals also con-

tamination in air, soil, and water is a global problem that is a growing threat to human beings. There are hundreds of sources of heavy metal pollution, including coal combustion in thermal power plants [4]. Bottom ash and fly ash produced during the combustion of coal contains several toxic heavy metals like arsenic (As), lead (Pb), nickel (Ni), zinc (Zn), nickel (Ni), etc. It is now a global concern to find environmentally friendly solutions for the safe disposal of industrial waste to sustain a cleaner and greener environment.

Coal ash is one of the biggest sources of industrial waste that is produced from power plant stations. Cheriaf et al. [5] stated that 1.2 million metric tons

\*To whom corresponding should be addressed.

Tel : +82-43-750-1399 E-mail : skkang@kgs.or.kr

of coal ash have been produced during the combustion of 2.9 million metric tons of coal. Coal is widely used in the production of electricity, steel and cement manufacturing and is, therefore, an important source of energy. However, based on Bajare et al. [6], several types of coal ash waste have been identified such as bottom ash, fly ash, boiler slag, flue gas, desulfurized material and etc. Coal bottom ash and boiler slag are coarse, granular, incombustible materials that are collected from the bottom of coal burning furnaces. The majority of coal bottom ash and boiler slag are produced at coal-fired electric utility generation stations, with some coming from coal-fired boilers or independent coal-burning electric generation facilities. The type of bottom ash or boiler slag produced depends on the type of coal-burning furnace.

Bottom ash is one of the well-known industrial waste that has been produced as a result of burning coal in a dry bottom pulverized coal boiler. Unburned material from a dry bottom boiler consists of about 20 percent bottom ash. Bottom ash is a porous, glassy, dark gray material with a grain size similar to that of sand or gravelly sand [7]. Although similar to natural fine aggregate, bottom ash is lighter and more brittle and has a greater resemblance to cement clinker [8]. Boiler slag is the molten inorganic material that is collected at the bottom of the boilers and discharged into a water-filled pit where it is quenched and removed as glassy particles resembling sand. When pulverized coal is burned in wet-bottom boilers (slag-tap boiler and the cyclone boiler), as much as 50 percent of the ash is retained in the slag tap furnace as boiler slag. In a cyclone furnace, 70 to 80 percent of the ash is retained as boiler slag, with only 20 to 30 percent leaving the furnace in the form of fly ash [7,8].

Huge amounts of limestone are quarried and used worldwide for construction and landscaping purposes. A large amount of waste is generated during cutting and sieving process of limestone which includes fragments, fine powder, and slurry. 60% to 70% of the stone is believed to be wasted in this process, of

which around 30% is believed to be fine powder [9]. A large amount of limestone waste generated from the processing has no useful utilization and is disposed of as waste, occasionally used for landfill purposes.

The products of the coal combustion process are flue gas and solid byproducts (e.g., fly ash particles, bottom ash, and boiler slag). Flue gas CO<sub>2</sub> emissions from coal-fired power plants totaled 1718 Mt in the USA in 2011 [10]. Addressing the continuous rise of atmospheric carbon dioxide levels has become a focus of global efforts. Research in carbon capture and storage (CCS) has increased substantially in the last decade [11,12]. Current carbon storage research has been primarily concentrated on sequestering CO<sub>2</sub> in underground geologic formations such as saline aquifers, depleted oil and gas fields, and unmiserable coal seams. These methods of geologic sequestration have the advantage of being the relatively low cost when separated from CO<sub>2</sub> capture, separation, and transportation. However, potential issues associated with sequestration in geologic formations include permanence, long-term monitoring, and verification, with many unknown effects and potential risks still to be determined [13,14]. An alternative to conventional geologic sequestration is carbon mineralization, where CO<sub>2</sub> is reacted with metal cations such as magnesium, calcium, and iron to form carbonate minerals.

The literature to date indicates that in the coming decades mineral carbonation can play an important role in rebalancing the global carbon cycle and providing a long-term carbon storage solution [15,16] and the carbonation process can reduced heavy metal from the carbonated materials. Heavy metal extraction should be considered seriously for usage of carbonated materials since carbonation seriously effects on precipitation of minerals and contaminant leaching through neutralization. To reduce the heavy metal leaching on the carbonation process is the pH neutralization and formation of new materials from the raw minerals. Lowing pH to 8~9 minimizes dissolution of metal oxides [17] and physical changes of the waste material structures and the extraction

characteristics and mechanical properties. The carbon dioxide source can be either pure CO<sub>2</sub> or any other CO<sub>2</sub>-rich gas such as certain industrial emissions. Consequently, using bottom ash CO<sub>2</sub> sequestration capacity to treat industrial emissions could be another interesting possibility of ash utilization. This process could both help reducing the greenhouse effect and reducing bottom ash storage duration by accelerating weathering reactions [18-21].

The focus of the research in this paper is aimed to CO<sub>2</sub> sequestration characteristics and capture potentials of those target waste materials such as coal-fired power plants bottom ash, Kanvera Reactor (KR) slag and lime waste particles and stabilization of toxic heavy metals from bottom ash sample were investigated.

## 2. EXPERIMENTAL PROCEDURE:

### 2.1. Materials and sample preparation

In this study, we chose pulverized coal (PC) power plant bottom ash sample, kanvera reactor (KR) slag and waste lime stone was used. After receiving the samples we dried the samples at room temperature for the removal of moisture from that samples. After drying, samples were grinded by using a comminution equipment and collected the fine powder size less than 75 $\mu$ m for reproducible experiments. Accelerated carbonation process was conducted through bench scale reactor for stabilizing the high content of hazardous heavy metals in coal bottom ash sample, and CO<sub>2</sub> sequestered in PC boiler bottom ash using with KR slag and waste lime stone as a calcium source. These experiments were conducted using a various condition with a solid-liquid ratio, temperature, and CO<sub>2</sub> concentrations.

In the accelerated carbonation process, gaseous CO<sub>2</sub> was injected into a hydrated bottom ash sample mixed with KR slag or calcined limestone as a calcium source as shown in Fig. 1. CO<sub>2</sub> sequestration process by carbonation method. In the carbonation

process, we used bottom ash mixed with KR slag (8:2 ratio) sample and bottom ash mixed with calcined lime (9:1 ratio) samples. These two samples were used for carbonation process to stabilized heavy metals and CO<sub>2</sub> sequestration process. The detailed experiment conditions were conducted with a liquid-solid ratio as 10-30 dm<sup>3</sup>/kg, conducted with temperature as 20 $^{\circ}$ C to 40 $^{\circ}$ C and CO<sub>2</sub> concentration as 10%, 30%, and 100%. Other conditions of the experiments used here were injection at a rate of 1L/min. The experiment of carbonation was terminated when the measured pH was below 7 and did not change any further. Two phases are possible in bench scale carbonation process (a) liquid phase as a calcium ion (Ca<sup>2+</sup>) source and (b) gas phase as carbonate ion (CO<sub>3</sub><sup>2-</sup>) source. In a short time, the gas and the liquid mix together and form a turbulent flow for optimum mass transfer; finally, this process leads to the formation of calcite crystals.

### 2.2. Carbonation Process:

In this carbonation process, the CaO was hydrated to form Ca(OH)<sub>2</sub> slurry and is shifted to the carbonation reactor chamber, the gaseous CO<sub>2</sub> was injected into the Ca(OH)<sub>2</sub> slurry. The general mechanism involved in the carbonation process can be expressed as follows:

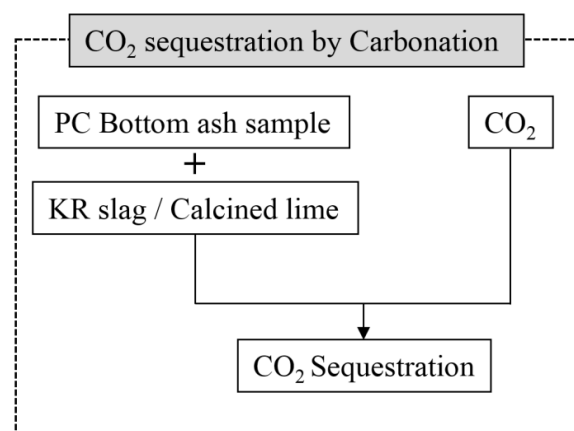
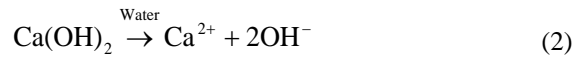
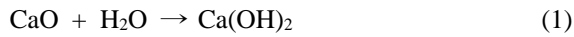
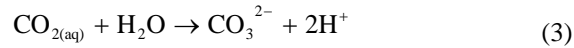


Fig. 1. CO<sub>2</sub> sequestration process by carbonation method.



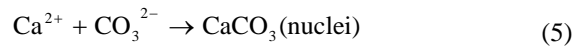
The dissociation of aqueous carbon dioxide,



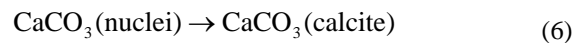
These processes produce a fast supersaturating ( $S_i$ ) of solution with respect to calcite,

$$S_i = \frac{(\text{Ca}^{2+})(\text{CO}_3^{2-})}{K_{sp}} > 1 \quad (4)$$

Where ( $\text{Ca}^{2+}$ ) and ( $\text{CO}_3^{2-}$ ) are the activities of calcium and carbonate ions in the solution, respectively, and  $K_{sp}$  is the thermodynamic solubility product of calcite.



Finally, the crystal growth occurs spontaneously until the equilibrium calcite and the solution is reached



The carbonation reaction starts from the hydration of carbon dioxide and the ionization of calcium hydroxide or calcium oxide, as shown in Eqs. (1), (2), (3), and (4). The aqueous carbonation of calcium hy-

droxide in contact with compressed CO<sub>2</sub> at moderate temperature allows the synthesis of fine particles of calcite. Carbonation is a strongly exothermic reaction. The reaction mechanism of calcite precipitation via aqueous carbonation of Ca(OH)<sub>2</sub> was then described by the global reaction.

### 3. RESULTS AND DISCUSSION:

#### 3.1. Characteristics of PC power plant bottom ash, KR slag, and calcined limestone powder:

X-ray fluorescence (XRF) and X-ray diffraction (XRD) were used in the analyses of the chemical compositions and crystalline structures of PC bottom ash, KR slag and calcined lime waste samples. Table 1 shows the chemical compositions PC power plant bottom ash sample. The major components of bottom ash are 57.75% SiO<sub>2</sub>, 21.29% Al<sub>2</sub>O<sub>3</sub>, 8.74% Fe<sub>2</sub>O<sub>3</sub>, 1.34% MgO and 4.31% of CaO. These XRF results indicated that the calcium source (4.31%) was very less amount present in the bottom ash sample.

The chemical compositions of KR slag results as shown in Table. 2. The major components of the KR slag are 61.84% of CaO, 6.94% of SiO<sub>2</sub>, 2.25% of Al<sub>2</sub>O<sub>3</sub>, 6.81% Fe<sub>2</sub>O<sub>3</sub> and 1.81% MgO are present remaining elements such as K<sub>2</sub>O, Na<sub>2</sub>O, TiO<sub>2</sub>, MnO, and P<sub>2</sub>O<sub>5</sub> are less than 1% (<1%) present in the sample. The results indicate that KR slag has the major calcium source, it more than 60% of CaO present in the sample.

**Table 1.** PC type power plant Bottom ash XRF Chemical analysis result (Unit: wt %)

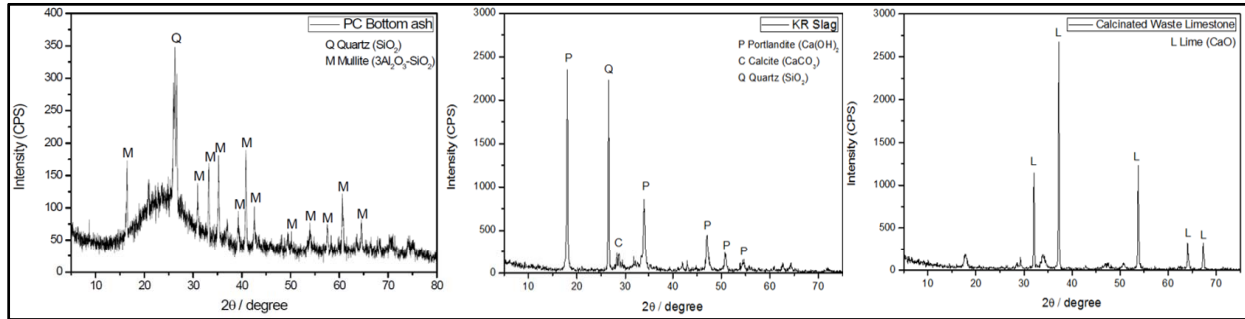
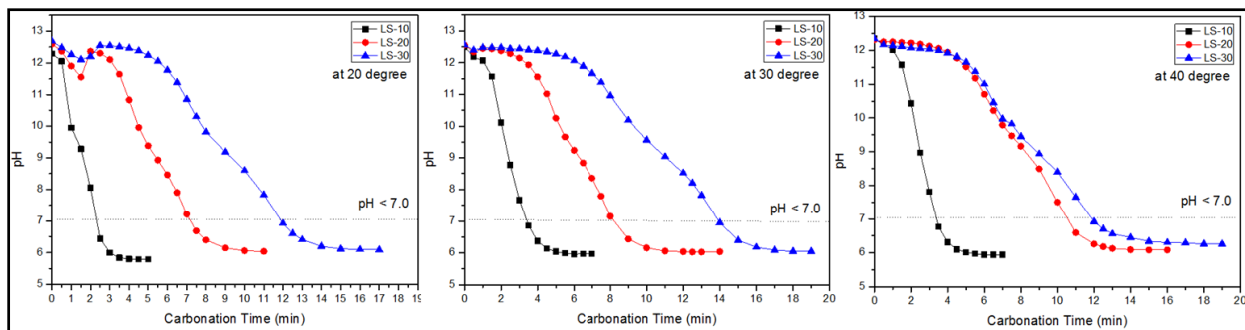
Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
PC Bottom ash	57.75	21.29	8.74	4.31	1.34	1.07	0.72	0.13	0.09	0.31

**Table 2.** KR (Kanvera Reactor) Slag XRF chemical analysis result (unit: wt %)

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
KR slag	6.94	2.25	6.81	61.84	1.81	0.11	0.02	0.19	0.85	0.21

**Table 3.** Calcined lime waste XRF chemical analysis (unit: wt %)

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	K <sub>2</sub> O	Na <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
Waste lime	4.67	2.64	0.44	81.10	1.99	0.26	0.12	0.10	0.30	0.02

**Fig. 2.** XRD analysis of PC power plant bottom ash, KR slag, and calcined waste limestone.**Fig. 3.** The carbonation process for different solid-liquid ratio (10-30 dm<sup>3</sup>/kg) with different temperature (20-40°C) at 100% CO<sub>2</sub> concentration.

The wasted calcined limestone chemical compositions as shown in Table. 3. The major components of the calcined limestone are 81.10% of CaO, 4.67% of SiO<sub>2</sub>, 2.64% of Al<sub>2</sub>O<sub>3</sub>, and 1.99% of MgO are present remaining elements such as Fe<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>O, Na<sub>2</sub>O, TiO<sub>2</sub>, MnO, and P<sub>2</sub>O<sub>5</sub> are less than 1% (<1%) are presented in waste limestone sample.

In Fig. 2 shows XRD results of PC power plant bottom ash, KR slag, and calcined waste limestone. The results indicated that high amount of quartz (SiO<sub>2</sub>) and less amount of lime (CaO) are present in PC power plant bottom ash sample. KR slag and calcined lime waste having a high amount of lime (CaO) and less amount of quartz (SiO<sub>2</sub>) are present.

### 3.2. CO<sub>2</sub> sequestration of PC power plant bottom ash along with KR slag.

In the CO<sub>2</sub> sequestration by accelerated carbonation process, we chose mixed pulverized coal (PC) power plant bottom ash with kanvera reactor (KR) slag (8:2 ratio) with fine particles (<75μm) and we can estimate the CO<sub>2</sub> sequestration potential of solid residues of before and after carbonation. The experiment conditions were conducted with a liquid-solid ratio as 10-30 dm<sup>3</sup>/kg, temperature as 20°C to 40°C and CO<sub>2</sub> concentration as 10%, 30%, and 100%. The experiment of carbonation was terminated when the measured pH was below 7 and did not change any further.

### 3.2.1. The effect of the liquid–solid ratio of coal bottom ash sample by carbonation:

The mixed PC power plant bottom ash sample was used for the carbonation process with different liquid-solid-ratio (10-30 dm<sup>3</sup>/kg) at different temperatures (20-40 °C). In Fig. 3, show that when the liquid-solid-ratio of bottom ash was increased, the carbonation reaction time also increased. These results indicated that the reaction was terminated quickly due to the low content of alkaline components that can react with CO<sub>2</sub> in the bottom ash sample.

### 3.2.2. Temperature effect (20–40°C) on the carbonation process with the different liquid–solid ratio (10–30 dm<sup>3</sup>/kg) of coal bottom ash sample.

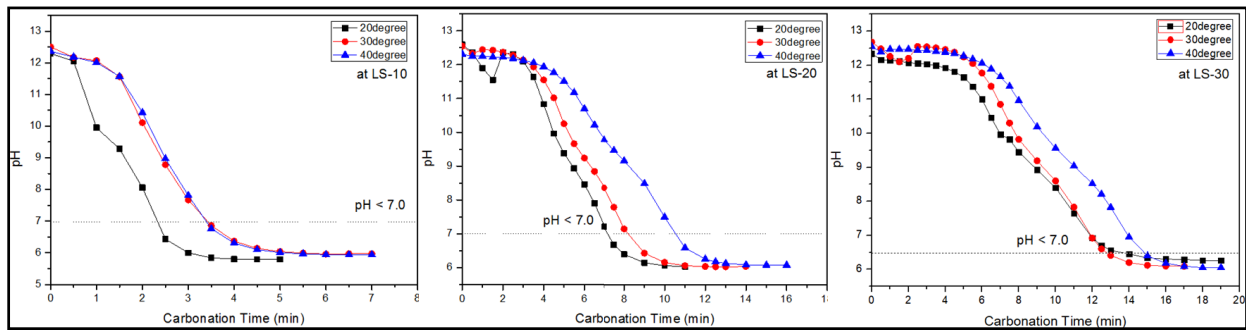
The carbonation process at different temperatures with different liquid-solid ratios as shown in Fig. 4, these results clearly indicated that when the liquid-solid ratio was increased along with temperature the carbonation time also increased due to the low solubility of a CO<sub>2</sub> gas at high temperatures. The carbonation process refers to carbon dioxide dissolved in a liquid, and the rate at which carbon dioxide dissolves or is soluble depends on temperature. When the temperature is raised, the rate of dissolution in liquid is decreased, and when the temperature is lowered the rate of dissolution in liquid is increased, because at high temperatures the molecules within that substance gain energy and move more rapidly and the dissolved carbon dioxide molecules move faster and escape the liquid more rapidly,

simultaneously the carbonation time also increased at high temperatures.

### 3.2.3. The effect of CO<sub>2</sub> concentrations (10, 30 and 100%) with different liquid–solid ratio (10–30 dm<sup>3</sup>/kg) for carbonation process at 20 °C temperature.

To evaluate the effect of CO<sub>2</sub> concentrations on the bottom ash carbonation process, several experiments were performed at 10% to 100% CO<sub>2</sub> concentrations. Fig. 5 shows the CO<sub>2</sub> concentrations effect of carbonation process with the different liquid-solid ratio at 20°C. From these figures was obvious that CO<sub>2</sub> concentrations greatly influences the reaction kinetics. When the 10% concentration of carbon dioxide was used for the carbonation with 10-30 dm<sup>3</sup>/kg liquid-solid (LS) ratio, the carbonation process was increased from 70min to 175min reaction time, these CO<sub>2</sub> concentrations were increased up to 30% CO<sub>2</sub> concentration along with 10-30 dm<sup>3</sup>/kg liquid-solid (LS) ratio, the carbonation process was increased from 15min to 75min reaction time and the pure 100% CO<sub>2</sub> concentrations were used with 10-30 dm<sup>3</sup>/kg liquid-solid (LS) ratio, the carbonation time was increased from 5min to 20min reaction time due to the less source of carbonate (CO<sub>3</sub><sup>2-</sup>) ions and increasing Ca<sup>2+</sup> ion source in the solutions are present along with increasing liquid-solid (LS) ratio from 10 to 30 dm<sup>3</sup>/kg in the solution for carbonation process.

These results also clearly indicated that the CO<sub>2</sub> concentrations were increased from 10% to 100%, the carbonation reaction time was drastically de-



**Fig. 4.** Temperature effect on the carbonation process with the different liquid-to-solid ratio at 100% CO<sub>2</sub> concentration.

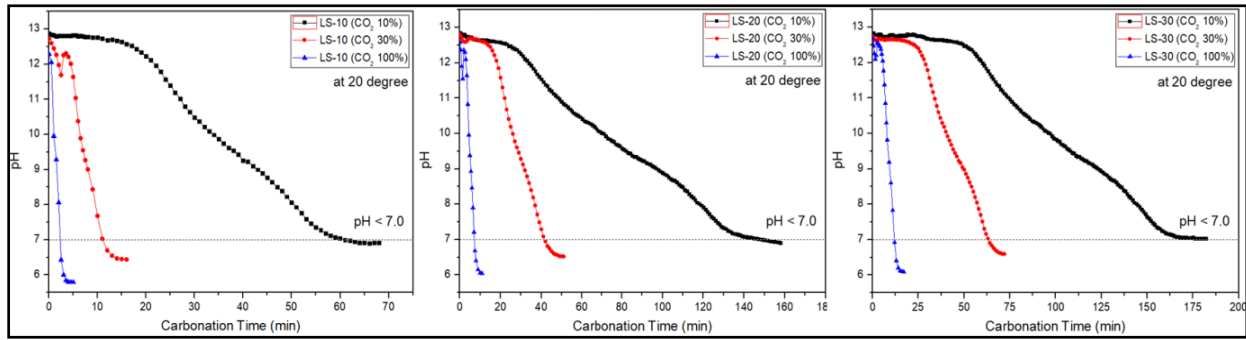


Fig. 5. CO<sub>2</sub> concentration effect of carbonation process with the different liquid-solid ratio at 20oC temperature.

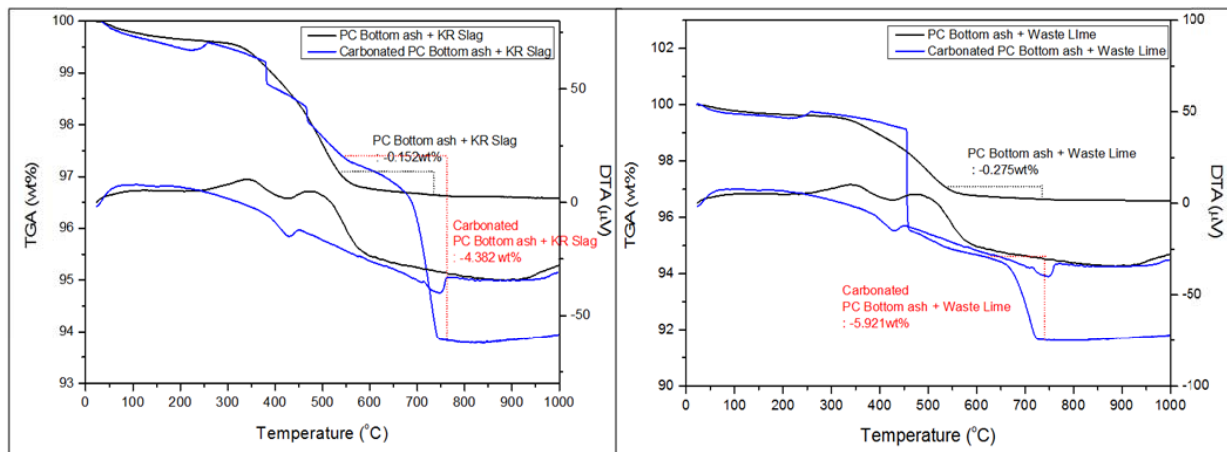


Fig. 6. TG / DTA results before and after carbonation of PC Bottom ash-KR Slag and PC Bottom ash-Calcined lime waste samples.

creased from 70min to 5min in 10 dm<sup>3</sup>/kg liquid-solid (LS) ratio solution, 150min to 10min in 20 dm<sup>3</sup>/kg liquid-solid (LS) ratio solution and 175min to 20min in 30 dm<sup>3</sup>/kg liquid-solid (LS) ratio solution by carbonation process, because the high amount of carbonate (CO<sub>3</sub><sup>2-</sup>) ions available in the carbonated solution.

**3.3. Thermal analysis:**

Samples were analyzed by simultaneous TG/DTA before and after a complete carbonation as shown in Fig.6. The TGA curves are plotted in wt% (in percentage) on the first axis and the second axis shows DTA (µV) value. The PC power plant bottom ash with KR slag (8:2) sample mass decreased by 0.152wt% before carbonation, and after carbonation, it decreased by 4.382wt%. As a result, CO<sub>2</sub> solid-

ification rate was 4.23% by carbonation, and 42.3g of CO<sub>2</sub> could be stored in 1kg of KR slag contained bottom ash sample. But in PC power plant bottom ash mixed with waste calcined lime (9:1 ratio) sample mass decreased by 0.275wt% before carbonation, and after carbonation, it decreased by 5.921wt%. As a result, CO<sub>2</sub> solidification rate was 5.646% by carbonation, and 56.46g of CO<sub>2</sub> could be stored in 1kg of calcined lime waste containing bottom ash sample, these results as shown in Table. 4, it indicates the specific CO<sub>2</sub> sequestration capacity was high in calcined lime waste containing bottom ash sample (9:1 ratio) was estimated by carbonation process.

**3.4. Leaching concentrations of heavy metals and stabilized with carbonation.**

Coal is a carbon-rich combustible material con-

taining organically bound mineral matter. This organic material is released during coal combustion to form an ash residue [22]. Various factors that control the concentrations of trace elements in the coal and ashes include element sources, modes of element occurrence, combustion conditions, volatilization-condensation mechanism, and particle size of the ash [23]. The PC power plant coal bottom ash has different concentration of heavy metals was observed as As, Pb, Cu, Cr, Cd, Ni, and Zn etc. In order to evaluate the environmental stability of PC coal bottom ash heavy metal content and leaching test were conducted before and after carbonation process. In the carbonation process, CO<sub>2</sub> gas was injected at a rate of 1L/min and 400rpm stirring speed at 20°C temperature was maintained and the carbonation process was terminated when the measured pH was below 7 and sample was filtered, the leachate solution was measured by ICP-MS for heavy metal analysis.

We investigated the leaching concentrations of heavy metals in PC power plant coal bottom ash sample. The heavy metals leaching characteristics are reported in mg/kg as shown in the Table. 5, for PC power plant coal bottom ash sample. The results indicated that Ni has been eluted in the leaching solution, after carbonation process these Ni heavy metal

are not eluted in the leaching process, it indicates Ni has been stabilized effectively by carbonation process.

#### 4. CONCLUSIONS

The effects of accelerated carbonation process have the major advantage of chemically binding CO<sub>2</sub> and at the same lowering the hazardous nature of bottom ash. This accelerated carbonation process can chemically block the leaching of Ni and other heavy metals. The CO<sub>2</sub> volume that can solidify in the material has been quantified and is on average 40-60g of CO<sub>2</sub> / kg of PC coal bottom ash along with KR slag or waste calcined limestone. Tests performed to improve the efficiency of the process showed that the CO<sub>2</sub> partial pressure can drastically modify the kinetics of the reaction: the higher the CO<sub>2</sub> partial pressure, the faster the reaction. However, it does not increase the solidified volume of CO<sub>2</sub>. Our research results show the carbonation studies using PC power plant bottom ash and CO<sub>2</sub> in order to increase the recycling percentage of the ash and reduce the concentration of atmospheric CO<sub>2</sub>. This process is an eco-friendly for the removal of heavy metals from PC power plant bottom ash samples.

**Table 4.** PC Bottom ash-KR Slag-complex treatment of waste limestone CO<sub>2</sub> before and after carbonation

Mixed samples with ratio	Before carbonation wt %	After carbonation wt%	CO <sub>2</sub> solidification rate (%)
PC Bottom ash : KR slag (8 : 2)	0.152	4.382	4.230
PC Bottom ash : Waste lime (9 : 1)	0.275	5.921	5.646

**Table 5.** The analysis result of heavy metal leaching of PC boiler bottom ash sample before and after carbonation process. (Unit: mg/L) (N.d. = Not detected).

Heavy metals		As	Pb	Cu	Cr	Cd	Ni	Zn
PC Bottom ash	Before carbonation	N.d.	N.d.	N.d.	N.d.	N.d.	0.01	N.d.
	After carbonation	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.	N.d.



## ACKNOWLEDGEMENTS

This study was supported by the Energy Technology Development Project [20141010101880] of the Korea Institute of Energy Technology Evaluation and Planning, financed by the Ministry of Trade, Industry and Energy.

## REFERENCES

1. M.C Han, D. Han and J.K. Shin, Use of bottom ash and stone dust to make lightweight aggregate. *Construction and Building Materials*, **99**, 192-199 (2015).
2. S. Shahidan, S.S.M. Zuki and N. Jamaluddin, Damage grading system for severity assessment on concrete structure, *Case Stud, Constr. Mater.*, **5**, 79-86, (2016).
3. C. Arenas, C. Leiva, L.F. Vilches and H. Cifuentes, Use of co-combustion bottom ash to design an acoustic absorbing material for highway noise barriers. *Waste Management*, **33**(11), 2316-2321 (2013).
4. Khan, S. A., Din, Z. U., Ihsanullah, Z. A., & Zubair, A. (2011). Levels of selected heavy metals in drinking water of Peshawar city. *International Journal of Science and Nature*, **2**, 648-652.
5. M. Cheriaf, J.C. Rocha and J. Pera, Pozzolanic properties of pulverized coal combustion bottom ash, *Cement and Concrete Reserach*, **29**(9),1387-1391, (1999).
6. D. Bajare, G. Bumanis, and L. Upeniece, Coal combustion bottom ash as microfiller with pozzolanic properties for traditional concrete, *Procedia Engineering*, **57**, 149-158, (2013).
7. Steam, its generation and use. 39th ed. New York: Babcock & Wilcox; 1978.
8. Rogbeck J, Knutz A. Coal bottom ash as light fill material in construction. *Waste Management* 1996; **16**(1-3):125-8.
9. Bonavetti, V., Donza, H., Mene´ndez, G., Cabrera, O., and Irassar, E.F. (2003). "Limestone filler cement in low w/c concrete: a rational use of energy." *Cement and Concrete Research*, Vol. 33, pp. 865-71.
10. U.S. Energy Information Administration. Monthly Energy Review October 2013. Available online: [http://www.eia.gov/totalenergy/data/monthly/pdf/sec12\\_9.pdf](http://www.eia.gov/totalenergy/data/monthly/pdf/sec12_9.pdf) (accessed on 5 October 2013).
11. IPCC, "Carbon Dioxide Capture and Storage," Cambridge University Press, Cambridge, U.K., 2005.
12. Global CCS Institute 2014, "The Global Status of CCS: 2014," Global Carbon Capture and Storage Institute Ltd., Melbourne, Australia, 2014.
13. K. Lackner and S. Brennan, "Envisioning carbon capture and storage: expanded possibilities due to air capture, leakage insurance, and C-14 monitoring," *Climate Change*, vol. 96, no. 3, pp. 357-378, 2009.
14. K. Lackner, S. Brennan, J. Matter, A. Park, A. Wright and B. Van Der Zwaan, "The urgency of the development of CO2 capture from ambient air," *Proceedings of the National Academy of Sciences*, vol. 109, no. 33, pp. 13156-13162, 2012.
15. A. Sanna, M. Uibu, G. Caramanna, R. Kuusik and M. M. Maroto-Valer, "A review of mineral carbonation technologies to sequester CO2," *Chemical Society Reviews*, vol. 43, p. 8049-8080, 2014.
16. S. R. Gislason and E. H. Oelkers, "Carbon Storage in Basalt," *Science*, vol. 344, no. 6182, pp. 373-374, 2014.
17. R.N.J. Comans, H.A. van der Sloot, and P.A. Bonouvrie, "Speciation of contaminants during leaching of MSWI bottom ash (in Dutch)," ECN-C-93-090, 1993.
18. S. Kaibouchi, P. Germain, Comparative study of physico-chemical and environmental characteristics of MSWI bottom ash resulting from classical and selective collection for a valorization in-road construction, in: G. Ortiz de Urbina, H. Goumans (Eds.), WASCON Progress on the Road to Sustainability, Fifth International Conference on the Environmental and Technical Implications of Construction with Alternative Materials, San Sebastian, Spain, 4-6 juin 2003, pp. 645-653.
19. S. Kaibouchi, M^achefer d'incin´eration d'ordures m´enag`eres: contribution `a l'´etude des

mécanismes de stabilisation par carbonatation et influence de la collecte sélective, Thèse de l'Institut National des Sciences Appliquées, 2003.

20. T. van Gerven, E. van Keer, S. Arickx, M. Jaspers, G. Wauters, C. Vandecasteele, Carbonation of MSWI-bottom ash to decrease heavy metal leaching, in view of recycling, *Waste Manage.* 25 (2005) 291-300.
21. E.J. Anthony, L. Jia, J. Woods, W. Roque, S. Burwell, Pacification of high calcic residues using carbon dioxide, *Waste Manage.* 20 (2000) 1-13.
22. Zandi, M., & Russell, N. V. (2007). Design of a leaching test framework for coal fly ash accounting for environmental conditions. *Environmental Monitoring Assessment*, 131, 509-526. <http://dx.doi.org/10.1007/s10661-006-9496-y>.
23. Ram, L. C., Masto, R. E., Srivastava, N. K., George, J., Selvi, V. A., Das, T. B., Pal, S. K., Maity, S., & Mohanty, D. (2015). Potentially toxic elements in lignite and its combustion residues from a power plant. *Environmental Monitoring Assessment*, 187, 4148. <http://dx.doi.org/10.1007/s10661-014-4148-0>