Chapter 12
Fly Ash, Bottom Ash, and Dust

Abstract Fly ashes, suspended in the exhaust gases, can be collected by electrostatic precipitators or baghouse filter. On the other hand, the portion of the non-combustible residues from combustion in an incinerator or furnace that fall by themselves to the bottom hopper of a furnace or incinerator is referred as bottom ash. Both the fly ash and bottom ash can be used in various applications, such as concrete production, embankments, cement clinkers, and road subbase construction. In this chapter, the physico-chemical properties of fly ash and bottom ash are illustrated. In addition, the challenges in direct utilization of ashes, such as heavy metal leaching, are discussed.

12.1 Introduction

Solid ashes, such as air pollution control (APC) residues, bottom ash, and dust, are typical by-products from industrial or combustion processes. Due to the wide varieties of input feedstocks in physico-chemical properties, the produced ashes may contain hazardous compounds which might be harmful to human health and ecosystem quality. APC residues are the solid output of the flue gas treatment equipment after incineration or combustion processes. Typically, they comprise the fly ash from incineration (fine particles) together with the reagents (such as lime and activated carbon) used in the treatment equipment. On the other hand, bottom ash will generate in the incineration or combustion (furnace), which is considered part of the non-combustible residue. It usually refers to coal combustion ash in an industrial context, or bottom ash in a municipal solid waste incinerator (MSWI).

In the following content, the physico-chemical properties of different types of ashes are illustrated. The challenges in direct utilization of the ashes are also addressed.

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12.2 Fly Ash

Fly ash (FA), called APC residues from combustion process, are classified as hazardous wastes according to the Commission Decision 2000/532/EC due to the character of fine particle size and the potential release of persistent organic pollutants (POPs), metals, and soluble salts [1, 2]. Thus, they may contain the following:

- Volatile contaminants: chlorides, metals, etc.,
- Compounds created in the incineration process: dioxins, etc., and
- Other materials from flue gas treatment process: sulfates, alkalinity, etc.

In general, the FA is captured by electrostatic precipitators or other particle filtration equipment such as baghouse filter. In the United Kingdom, FA is also referred as pulverized fuel ash, which is mainly the product of coal combustion. In the USA, coal FA can be divided into two categories: (1) class C or (2) class F in accordance with the ASTM C618. The primary difference between the two US classifications of coal FA is the total content of silica, alumina, and ferrite in the material. Typically, the class C FA (FA-C) has much higher calcium content than class F FA (FA-F) [3]. This excess content of calcium is responsible for the self-cementing nature of FA-C as the principal reactive phases of FA-C are anhydrite ($CaSO_4$) and lime (CaOH).

12.2.1 Physico-chemical Properties

Table 12.1 presents the chemical properties of various types of FA used in the literature and its associated CO_2 capture capacity. FA is a heterogeneous material, with a spherical shape in size from 0.5 to 300 μm. According to the XRF results, the chemical composition of FA varies widely depending on the source and on particle sizes. For example, the chemical composition of fresh by-product ash consists mainly of CaO ($\sim$62.8%) and SO_3 ($\sim$31.0%). The mineral composition of FA includes merwinite [$(Ca_3Mg)(SiO_2)_4$], periclase (MgO), anhydrite [$Ca(SO)_4$], stishovite (SiO_2), and calcite ($CaCO_3$), where $Ca(SO)_4$ is the main phase. Therefore, the SO_3 composition in the fresh FA is mainly related to $CaSO_4 \cdot 2H_2O$ (gypsum), which has a profound effect on the initial cement chemical as well as mechanical strength.

In the fresh FA, Ca–Mg–Si oxide is typically present in significant quantities [4]. The contents of MgO, free-CaO, and $Ca(OH)_2$ in the fresh FA are generally related to a poor durability of cement mortar (e.g., autoclave expansion).

12.2.2 Challenges in Direct Utilization

During combustion in the boiler, a significant amount of limestone ($CaCO_3$) is introduced to suppress sulfur-species pollution from petroleum coke. Thus, the

Table 12.1 Chemical properties of various types of fly ash (FA) used in the literature and its associated CO_2 capture capacity

Items[a]	Components (%)	Coal FA (Victorian)	Coal FA	MSWI-FA	By-product lime ash [1]
XRF (solid phase)	SiO_2	58.6–60.0	51.2	9.2–13.0	3.08
	CaO	5.9–7.5	9.2	24.8–29.7	62.8
	Al_2O_3	19.1–19.7	26.0	2.1–2.5	1.01
	Fe_2O_3	4.7–5.4	2.4	11.1–23.0	0.70
	Na_2O	0.7–1.0	0.5	6.5–9.0	0.06
	P_2O_5	–	0.7	0.03	–
	MgO	~3.9	2.4	13.0–25.5	0.83
	SO_3	–	0.4	12.8–15.0	31.0
	K_2O	1.0–2.0	0.8	0.4–0.5	0.43
Chemical analysis	*f*-CaO	–	–	–	11.4
	$Ca(OH)_2$	–	–	–	3.42
Thermal analysis	$CaCO_3$	<0.1	–	–	–
	LOI	0.6	–	–	–

[a] Victorian brown coal fly ash (VBC-FA); Fly ash (FA)

fresh FA contains a large amount of gypsum ($CaSO_4$) and calcium oxide (free-CaO). Typically, the FA generated from a circular fluidized-bed (CFB) boiler is considered as a pozzolanic constituent. It has been widely used as supplementary cementitious materials (SCMs) or fine aggregates in blended cement [5, 6]. In another approach, the fresh FA can be used as a soil modification material for the following: (1) increasing strength, (2) enhancing load carrying capacity, and (3) reducing the potential volume change of soil [7].

Due to their high chemical activity, stabilization processes for fresh FA are required prior to further utilization in civil engineering [8, 9]. These APC residues, such as fly ash, are currently handled entirely by cement solidification and chemical agent stabilization treatments and then placed in sanitary landfills [10]. Several researches have applied highly pure CO_2 as curing atmosphere for FA-based cement mortar to eliminate free-CaO content and to enhance initial strength development [9, 11, 12].

12.3 Bottom Ash

Bottom ash (BA) is part of the non-combustible residues from combustion in an incinerator or furnace. The portion of the residues that fall by themselves to the bottom hopper of an incinerator or furnace is referred as BA. Usually, the BA was generated in large quantities from a municipal solid waste incinerator (MSWI). Incineration is an environmental-friendly treatment and management option to dispose municipal solid waste (MSW), especially where recycling or reuse is not possible. The MSWI can provide several advantages [1, 13, 14]:

- Mass and volume reductions of original waste can be up to 85 and 95%, respectively.
- Separation in fractions of different residues (e.g., ferrous metals, nonferrous metals, and granulate fractions) and the possibility of waste-to-resource conversion.
- It provides disinfection, reduction of organic matter.
- It can offer possibility of energy recovery.
- Fly ash (FA), or so-called air pollution control (APC) ash and

The combustion of MSW in incinerators would result in gaseous effluent containing approximately 12 vol.% CO_2 and two solid waste streams [15]:

- Fly ash (FA), or so-called air pollution control (APC) ash and
- Bottom ashes (BA).

Despite the significant volume reduction of MSW by incineration, the produced amounts of solid residues are still substantial. For each ton of MSW mass incinerated, approximately 35 kg of FA and 160 kg of BA are produced. In other words, these solid wastes would be up to a mass fraction of 20% from the original MSW [15, 16]. Particularly, the MSWI-BA accounts for 80–90% of the total mass of the MSWI residues [17]. In Taiwan, there are currently 24 large-scale MSW incinerators commercialized, with an annual incinerated MSW around 5.93 million tons in the years of 2002–2009 [10].

12.3.1 Physico-chemical Properties

MSWI-BA is a heterogeneous mixture of slag including ferrous and nonferrous metals, ceramics, and other non-combustible materials. The elemental composition of MSWI-BA depends primarily on the composition of the waste input, which may vary with location, season, and recycling schemes in operation [18, 19]. Table 12.2 presents the physicochemical properties of MSWI-BA. The major elements in MSWI-BA are O, Cl, Ca, Si, Al, Fe, Na, K, Mg, and C, with trace elements including Cu, Zn, S, Pb, Cr, Ni, Sn, Mn, Sb, V, and Co [1, 19]. According to the XRF analysis, the major components in the MSWI-BA are SiO_2, CaO, Al_2O_3, and Fe_2O_3, while the trace compounds are Na_2O, MgO, P_2O_5, TiO_2, and SO_3.

Mineralogical studies indicate that the main crystalline phases of MSWI-BA are typically [18, 19] as follows:

- Silicate:
  - Quartz [SiO_2],
  - Gehlenite [$Ca_2Al_2SiO_7$],
  - Olivine [$(Mg, Fe)_2SiO_4$],
  - Epidote (Al–Ca–Fe–SiO_2),

Table 12.2 Summary of physico-chemical properties of MSWI-BA [14]

Properties	Items		Fresh MSWI-BA		
			<125 μm	125–350 μm	350–500 μm
Physical	True density[a] (g cm^{-3})		2.70	2.73	2.78
	Mean diameter (μm)		59.6	175.8	501.5
	Median diameter (μm)		45.1	164.9	513.5
	BET surface area[a] (m^2 g^{-1})		6.63 ± 0.02	4.00 ± 0.02	3.51 ± 0.01
	Langmuir surface area[1] (m^2 g^{-1})		9.31 ± 0.30	5.57 ± 0.20	4.87 ± 0.17
Chemical	XRF	SiO_2 (%)	44.9	50.7	45.0
		CaO (%)	21.1	16.4	18.3
		Al_2O_3 (%)	9.3	8.7	9.5
		Fe_2O_3 (%)	8.5	9.3	11.8
		Na_2O (%)	5.0	5.9	5.2
		P_2O_5 (%)	2.6	2.3	2.6
		MgO (%)	2.1	1.9	2.1
		TiO_2 (%)	1.4	1.2	1.4
		SO_3 (%)	1.3	0.8	0.9
		K_2O (%)	0.9	0.8	0.8
	TGA	$CaCO_3$ (%)	7.07 ± 0.32	2.57 ± 0.02	3.38 ± 0.55
	Chem.[b]	f-CaO (%)	0.07	0.00	0.07

[a]Analyzed by Particulate Technology Laboratory, NTU. [b]Chemical analysis.

  - Augite [$(Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)_2O_6$], and
  - Pigeonite (Al–Ca–Fe–Mg–Mn–Ti–Na–SiO_2).
- Sulfate:
  - Anhydrite [$CaSO_4$],
  - Ettringite [$Ca_6Al_2(SO_4)_3(OH)$], and
  - Gypsum [$CaSO_4 \cdot 2H_2O$].
- Carbonate:
  - Calcite [$CaCO_3$] and
  - Aragonite [$CaCO_3$].
- Iron oxide:
  - Hematite [Fe_2O_3] and
  - Magnetite [Fe_3O_4].
- Others trace amounts:
  - Tassieite (Ca–Fe–Mg–Na–P–OH) and
  - Ktenasite (Cu–H–O–S–Zn).

Quartz was found to be the main component in MSWI-BA. Even though $Ca(OH)_2$ was not identified by the XRD measurements, Ca–Al–Si oxide and Ca–Na–Si oxide were present in significant quantities [14]. Calcium-bearing compounds in fresh MSWI-BA are primarily composed of various types of oxides with silicates that contain other metals, such as Fe and Al metals.

With the specific chemical characterizations of MSWI-BA, it exhibits its potential CO_2 fixation capability due to its calcium content and alkaline properties. In addition, the mineral carbonation of MSWI-BA can immobilize heavy metals and effectively prevent their leaching, especially for Cr, Cu, Pb, Zn, and Sb [1, 17, 18].

12.3.2 Challenges in Treatment, Disposal, and/or Utilization

Bottom ash accounts for 80–90% of the total weight of the MSW in incinerators [17]. The available and common methods for disposal of ashes from the MSW are landfill (82%), recycling or composting (11%), and thermal treatment (7%) [20]. According to the European Waste Catalogue, MSWI-BA is typically classified as a non-hazardous waste. Therefore, it is currently being utilized as an aggregate substitute in road bases and bituminous pavement in European countries [19, 21]. Similarly, in Taiwan, the BA also is classified as a general (non-hazardous) industry waste. Although BA can pass nearly all of the standards of the toxicity characteristic leaching procedure (TCLP), its high chloride content makes its reuse limit [10]. In addition, the potentially high leaching of salts and other elements would increase the pretreatment cost for further utilization [1].

12.4 Electric Arc Furnace Dust (EAFD)

Electric arc furnace dust (EAFD) is considered to be a hazardous waste because of its chemically, physically, and mineralogically complex, and the presence of lead, cadmium, chromium, and zinc [22]. Since EAFD is generated when automobile scrap is remelted in an electric arc furnace, the properties of each dust are site-specific and depend upon the scrap composition and the furnace operating practice [22]. Generally, 10–20 kg of EAFD would be generated for per ton of steel produced [22].

Typically, the major elements in fresh EAFD include zinc, iron, and calcium ions. The zinc element is found in the form of zincite (ZnO), zinc ferrite/franklinite ($ZnFe_2O_4$), zinc chloride ($ZnCl_2$), and diiron zinc tetraoxide (Fe_2ZnO_4). The remaining iron may be present as hematite (Fe_2O_3) and magnetite (Fe_3O_4), or in combination with lime (CaO) as calcium ferrites, or with silica as iron silicates [22]. Other elements are found in low concentrations, such as magnesium (Mg), lead (Pb), silicon (Si), aluminum (Al), manganese (Mn), chromium (Cr), nickel (Ni), copper (Cu), and cadmium (Cd). For example, the lead is typically presented as lead oxide (PbO) and lead chloride ($PbCl_2$). It is noted that the amounts of zinc and lead in the EAFD are economically valuable, while the iron is usually not worth recovering [22].

12.5 Challenges and Perspectives in Ash Utilization

Both the fly ash and bottom ash can be used in various applications, such as concrete production, embankments, cement clinkers, mine reclamation, and road subbase construction. Processes using fresh fine FA as alternative binders and replacement of Portland cement in concrete have been widely developed and deployed, especially in the USA, to reduce the energy and resource consumption, as well as the CO_2 emission for concrete and cement production.

Despite the fact that the FA usually replaces no more than 25% of the Portland cement in concrete, research has successfully demonstrated the use of 100% fly ash concrete with glass aggregate to construct a building by Montana State University [23]. However, the challenges in the substitution using fresh FA or BA in cement and/or concrete are mainly related to early strength development. Engineering experience indicates that, in the case of 50% clinker replacement by fresh FA, the early strength of concrete would be reduced dramatically [24]. To overcome the above challenges, accelerated carbonation process should be an effective method for stabilizing FA and BA; meanwhile, permanently storing CO_2 as solid carbonates [16, 25, 26].

12.5.1 Accelerated Carbonation with Flue Gas CO_2

CO_2 in the flue gas can react with calcium-bearing materials to form stable and insoluble calcium carbonates. Beside the calcium oxide (CaO), magnesium oxide (MgO) also can be the favorable metal oxides in reacting with CO_2. In many countries (such as France and Canada), natural aging and/or ambient air carbonation are the standard practice to stabilize alkaline fly ash and bottom ash [15, 27, 28]. As a result, carbonation of municipal solid waste has recently been receiving more attention due to their availability, low cost, and high CaO and/or MgO contents [16, 29]. Figure 12.1 shows the photographs of MSWI-BA (left) before and (right) after carbonation. The accelerated carbonation can improve the chemical and physical characteristics of solid wastes and facilitate their reuse in a various applications, such as synthesis of construction materials [14, 18]. Since accelerated carbonation is an exothermic process, additional heat input and energy cost could be reduced [30].

After carbonation, both calcite ($CaCO_3$) and quartz (SiO_2) are found to be a major component of the carbonated MSWI-BA, according to the XRD analysis shown in Fig. 12.2 [14]. The calcium-bearing species in MSWI-BA are primarily

Fig. 12.1 Photograph of municipal solid waste incinerator bottom ash (*left*) before and (*right*) after carbonation

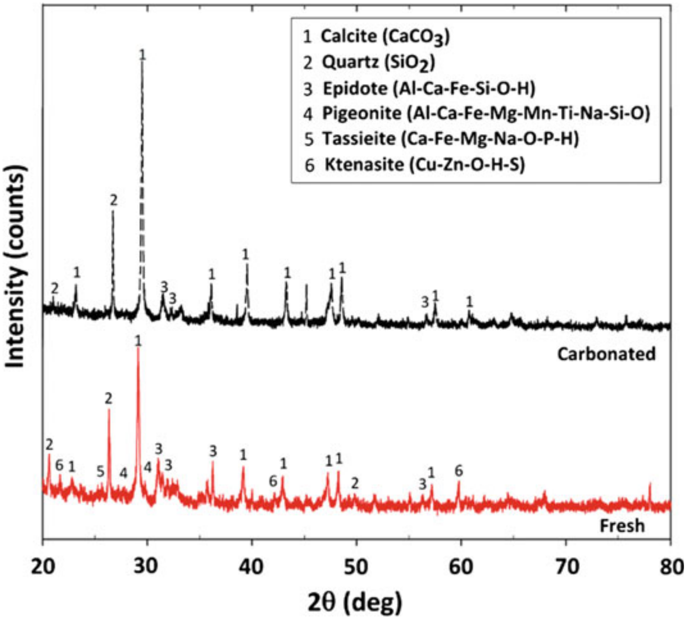

Fig. 12.2 X-ray diffraction pattern of fresh and carbonated municipal solid waste incinerator bottom ashes. Reprinted by permission from Macmillan Publishers Ltd: Ref. [14], copyright 2015

composed of various types of silicates, such as CaO–Al–silicates and CaO–Fe–silicates. The dissociation of calcium-bearing components in the fresh MSWI-BA should occur after introducing the ash into the solution. The calcium ions react with carbonate ions (CO_3^{2-}) under an alkaline condition, leading to the formation of $CaCO_3$ upon introducing of CO_2 into the reactor. Thus, the leaching concentration of calcium ions from MSWI-BA into the solution is an important indicator for accelerated carbonation.

Table 12.3 Comparison of performance and operating conditions using municipal solid waste residues in the literature

Material type	Method[a]	Operating conditions[b]					Performances	
		Liquid types[c]	Pres. (bar)	L/S ratio (mL/g)	Temp. (°C)	Time (min)	Carbonation conversion (%)	Capture capacity per kg waste
Fly ash [31]	AC	DI water	3	0.3	8-42	4320	35.1	100 g CO_2
Fly ash [32]	AC	DI water	1	4	25	14,400	28.8	120 g CO_2
Fly ash [2]	AC	DI water	1	2.5	20	180	–	200 g CO_2
Bottom ash [15]	DC	Moist. = 20%	17	–	25	180	67.7	87 g CO_2
Bottom ash [18]	DC	Moist. = 65%	3	0.3–0.4	25	1440	–	32 g CO_2
Bottom ash [14]	AC	CRW	1	10	25	120	90.7	102 g CO_2

[a] *AC* aqueous carbonation; *DC* dry carbonation. [b] all experiments were conducted in 100% CO_2 gas. [c] *CRW* cold-rolling mill wastewater

Table 12.3 presents the performance of carbonation using MSWI residues, such as APC and bottom ash, in the literature. The dry carbonation process possessed a relatively low capture capacity of 0.08–0.09 kg CO_2/kg MSWI-BA (equivalent to 24 L CO_2/kg BA) [15]. In converse, the aqueous carbonation of MSWI-FA offers a CO_2 fixation capacity of 0.10–0.12 kg per kg ash (corresponding to an average weight gain of 7–12%) under a reaction time of 72–240 h. [31, 32]. Similarly, the aqueous carbonation process using MSWI-APC, a CO_2 capacity of 200 g CO_2 per kg APC can be achieved at a relatively mild operating condition (i.e., 20 °C for 3 h) [2]. This might also be attributed to the active chemical properties of MSWI fly ash.

12.5.2 Heavy Metal Leaching Potential

Several heavy metals, such as lead (Pb), barium (Ba), mercury (Hg) and arsenic (As), can be potentially leached out from the solid matrix with the fresh FA or BA [4]. Therefore, several research has focused on the effect of accelerated carbonation on the leaching behavior of trace heavy metals from FA and/or BA. It indicates that heavy metals can be immobilized effectively by accelerated carbonation, especially Cr, Cu, Pb, Zn, and Sb are the most significant [1, 17, 18]. Cd and Pb have a strong affinity with calcium carbonate and also form complexes with Fe and Al (hydr) oxides [15].

For example, Sb leaching in fresh and carbonated BA (sand fraction) is solubility-controlled by $Ca_{1.13}Sb_2O_6(OH)_{0.26}\cdot 0.74H_2O$ [13]. As carbonation proceeds (i.e., lowering pH), preferential Ca-leaching from romeites and a higher Sb solubility were observed [13]. Accelerated carbonation may thus only be successful at reducing Sb leaching from MSWI-BA if relatively low pH values are obtained where adsorption to iron and aluminum oxides surfaces may again reduce Sb solubility [13]. In addition, immobilization of Sb could also be achieved by combining with other process (e.g., sorbent adding) during carbonation reaction [2]. Furthermore, accelerated carbonation has proved to be an ineffective method for the demobilization of chloride (Cl^-) and sulfate (SO_4^{2-}) ions [1].

References

1. Todorovic J, Ecke H (2006) Demobilisation of critical contaminants in four typical waste-to-energy ashes by carbonation. Waste Manag 26(4):430–441. doi:10.1016/j.wasman.2005.11.011
2. Cappai G, Cara S, Muntoni A, Piredda M (2012) Application of accelerated carbonation on MSW combustion APC residues for metal immobilization and CO_2 sequestration. J Hazard Mater 207–208:159–164. doi:10.1016/j.jhazmat.2011.04.013
3. Paris JM, Roessler JG, Ferraro CC, DeFord HD, Townsend TG (2016) A review of waste products utilized as supplements to Portland cement in concrete. J Clean Prod 121:1–18. doi:10.1016/j.jclepro.2016.02.013

4. Pan S-Y, Hung C-H, Chan Y-W, Kim H, Li P, Chiang P-C (2016) Integrated CO_2 fixation, waste stabilization and product utilization via high-gravity carbonation process exemplified by CFB fly ash. ACS Sustain Chem Eng
5. Snellings R, GIlles M, Elsen J (2012) Supplementary cementitious materials. In: Broekmans MATM, Pollmann H (eds) Reviews in mineralogy and geochemistry, vol 74. Mineralogical society of America, pp 211–278
6. Çiçek T, Çinçin Y (2015) Use of fly ash in production of light-weight building bricks. Constr Build Mater 94:521–527. doi:10.1016/j.conbuildmat.2015.07.029
7. Tsiridis V, Petala M, Samaras P, Sakellaropoulos GP (2015) Evaluation of interactions between soil and coal fly ash leachates using column percolation tests. Waste Manage 43:255–263. doi:10.1016/j.wasman.2015.05.031
8. Hu Y, Zhang P, Li J, Chen D (2015) Stabilization and separation of heavy metals in incineration fly ash during the hydrothermal treatment process. J Hazard Mater 299:149–157. doi:10.1016/j.jhazmat.2015.06.002
9. Morandeau A, Thiéry M, Dangla P (2015) Impact of accelerated carbonation on OPC cement paste blended with fly ash. Cem Concr Res 67:226–236. doi:10.1016/j.cemconres.2014.10.003
10. Yang R, Liao WP, Wu PH (2012) Basic characteristics of leachate produced by various washing processes for MSWI ashes in Taiwan. J Environ Manage 104:67–76. doi:10.1016/j.jenvman.2012.03.008
11. Zhang F, Mo L, Deng M (2015) Mechanical strength and microstructure of mortars prepared with MgO-CaO-Fly ash-Portland cement blends after accelerated carbonation. J Chin Ceram Soc 43(8):1–8. doi:10.14062/j.issn.0454-5648.2015.08.01
12. Mo L, Zhang F, Deng M (2015) Effects of carbonation treatment on the properties of hydrated fly ash-MgO-Portland cement blends. Constr Build Mater 96:147–154. doi:10.1016/j.conbuildmat.2015.07.193
13. Cornelis G, Van Gerven T, Vandecasteele C (2012) Antimony leaching from MSWI bottom ash: modelling of the effect of pH and carbonation. Waste Manage 32(2):278–286. doi:10.1016/j.wasman.2011.09.018
14. Chang EE, Pan SY, Yang L, Chen YH, Kim H, Chiang PC (2015) Accelerated carbonation using municipal solid waste incinerator bottom ash and cold-rolling wastewater: performance evaluation and reaction kinetics. Waste Manage 43:283–292. doi:10.1016/j.wasman.2015.05.001
15. Rendek E, Ducom G, Germain P (2006) Carbon dioxide sequestration in municipal solid waste incinerator (MSWI) bottom ash. J Hazard Mater 128(1):73–79. doi:10.1016/j.jhazmat.2005.07.033
16. Bobicki ER, Liu Q, Xu Z, Zeng H (2012) Carbon capture and storage using alkaline industrial wastes. Prog Energy Combust Sci 38(2):302–320. doi:10.1016/j.pecs.2011.11.002
17. Arickx S, Van Gerven T, Vandecasteele C (2006) Accelerated carbonation for treatment of MSWI bottom ash. J Hazard Mater 137(1):235–243. doi:10.1016/j.jhazmat.2006.01.059
18. Fernandez Bertos M, Li X, Simons SJR, Hills CD, Carey PJ (2004) Investigation of accelerated carbonation for the stabilisation of MSW incinerator ashes and the sequestration of CO_2. Green Chem 6(8):428. doi:10.1039/b401872a
19. Teir S (2008) Fixation of carbon dioxide by producing carbonates from minerals and steelmaking slags. Helsinki University of Technology
20. Fernandez Bertos M, Simons SJ, Hills CD, Carey PJ (2004) A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO_2. J Hazard Mater 112(3):193–205. doi:10.1016/j.jhazmat.2004.04.019
21. Astrup T, Mosbaek H, Christensen TH (2006) Assessment of long-term leaching from waste incineration air-pollution-control residues. Waste Manage 26(8):803–814. doi:10.1016/j.wasman.2005.12.008
22. Pickles CA (2009) Thermodynamic analysis of the selective chlorination of electric arc furnace dust. J Hazard Mater 166(2–3):1030–1042. doi:10.1016/j.jhazmat.2008.11.110

23. Hasanbeigi A, Price L, Lin E (2012) Emerging energy-efficiency and CO_2 emission-reduction technologies for cement and concrete production: A technical review. Renew Sustain Energy Rev 16(8):6220–6238. doi:10.1016/j.rser.2012.07.019
24. Crow JM (2008) The concrete conundrum. Chem World 62–66
25. Pan SY, Chiang PC, Chen YH, Tan CS, Chang EE (2013) Ex Situ CO_2 capture by carbonation of steelmaking slag coupled with metalworking wastewater in a rotating packed bed. Environ Sci Technol 47(7):3308–3315. doi:10.1021/es304975y
26. Lackner KS, Wendt CH, Butt DP, Joyce EL, Sharp DH (1995) Carbon dioxide disposal in carbonate minerals. Los Alamos National Laboratory, Los Alamos, NM, USA
27. Santos RM, Mertens G, Salman M, Cizer O, Van Gerven T (2013) Comparative study of ageing, heat treatment and accelerated carbonation for stabilization of municipal solid waste incineration bottom ash in view of reducing regulated heavy metal/metalloid leaching. J Environ Manage 128:807–821. doi:10.1016/j.jenvman.2013.06.033
28. Assamoi B, Lawryshyn Y (2012) The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion. Waste Manage 32(5):1019–1030. doi:10.1016/j.wasman.2011.10.023
29. Pan S-Y, Chang EE, Chiang P-C (2012) CO_2 capture by accelerated carbonation of alkaline wastes: a review on its principles and applications. Aerosol Air Qual Res 12:770–791. doi:10.4209/aaqr.2012.06.0149
30. Eloneva S, Teir S, Salminen J, Fogelholm CJ, Zevenhoven R (2008) Fixation of CO_2 by carbonating calcium derived from blast furnace slag. Energy 33(9):1461–1467
31. Li X, Bertos MF, Hills CD, Carey PJ, Simon S (2007) Accelerated carbonation of municipal solid waste incineration fly ashes. Waste Manage 27(9):1200–1206. doi:10.1016/j.wasman.2006.06.011
32. Wang L, Jin Y, Nie Y (2010) Investigation of accelerated and natural carbonation of MSWI fly ash with a high content of Ca. J Hazard Mater 174(1–3):334–343. doi:10.1016/j.jhazmat.2009.09.055