Supplementary Content

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

Rafael M. Santos, Gilles Mertens, Muhammad Salman, Özlem Cizer, Tom Van Gerven

KU Leuven, Leuven, Belgium

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Equations:

Volume moment mean diameter ($D[4,3]$):

$$D[4,3] = \lim_{\Sigma \rightarrow 0} \left\{ \sum_{all...x} [m_x \cdot (x - D[4,3])] \right\}$$

where: m_x is the mass fraction of each particle size fraction; and x is the particle size fraction (mm).

Surface area moment mean diameter ($D[3,2]$):

$$D[3,2] = \frac{1}{\sum_{all...x} \left(\frac{m_x}{x} \right)}$$

where: m_x is the mass fraction of each particle size fraction; and x is the particle size fraction (mm).

Determination of CaCO_3 content from TGA measurement:

$$w_{\text{CaCO}_3} = \left[(m_{500^\circ\text{C}} - m_{800^\circ\text{C}}) / m_{20^\circ\text{C}} \right] \cdot MW_{\text{CaCO}_3} / MW_{\text{CO}_2}$$

where: w_{CaCO_3} is the mass fraction of CaCO_3 in the sample, m are the sample masses at different temperatures, and MW are molecular weights.

Table SC-1

Semi-quantitative SEM-EDX analyses (in wt.%) of fresh B and F bottom ash samples. In Figs. 2 and 3 the positions (e.g. A1, A2...) where EDX-analyses were performed are indicated.

Analysis point		C	O	Si	Al	Ca	Mg	Na	K	P	S	Cl	Fe	Ti	Mo	V
B, fresh sample (Fig. 2)																
A	1	10.9	25.2	7.1	0.8	8.2	0.7	-	-	0.3	0.4	0.3	46.0	-	-	-
	2	16.0	41.0	41.6	-	0.6	-	-	-	-	-	0.8	-	-	-	-
	3	11.6	26.9	12.7	2.0	9.7	0.7	0.6	-	0.4	0.9	0.4	33.2	0.9	-	-
	4	18.8	39.1	1.7	1.2	33.6	1.2	0.9	0.7	0.6	0.9	1.3	-	-	-	-
B	1	20.3	41.0	0.2	-	21.8	0.7	1.4	-	13.6	0.2	0.9	-	-	-	-
	2	22.4	38.5	0.4	0.2	22.3	0.5	1.6	-	12.6	0.3	1.1	-	-	-	-
	3	9.7	22.7	-	-	-	-	-	-	-	-	-	67.6	-	-	-
	4	15.2	23.1	4.4	1.3	26.6	0.6	1.3	1.2	0.5	0.3	1.3	20.1	3.8	-	0.4
	5	26.7	34.7	0.4	7.8	18.2	0.3	1.8	0.9	-	4.6	4.6	-	-	-	-
C	1	14.0	36.5	21.2	6.0	9.1	2.0	2.9	3.2	0.8	-	0.6	2.2	1.7	-	-
	2	20.5	28.6	11.8	4.2	24.9	0.7	0.8	-	0.0	0.0	0.6	3.3	4.5	-	0.2
D	1	14.2	28.6	13.5	3.4	10.7	1.2	1.6	1.0	1.0	0.3	0.5	24.1	-	-	-
	2	11.1	23.4	0.3	1.6	-	1.0	-	-	-	-	-	61.7	0.8	-	-
F, fresh sample (Fig. 3)																
A	1	19.7	45.7	25.4	-	3.4	1.8	4.0	-	-	-	-	-	-	-	-
	2	49.5	29.0	3.4	-	3.8	-	5.1	-	-	3.5	5.9	-	-	-	-
	3	27.3	43.9	19.7	0.4	2.2	1.3	5.1	-	-	-	-	-	-	-	-
	4	34.4	55.9	0.8	-	6.8	0.4	1.7	-	-	-	-	-	-	-	-
B	1	21.7	38.2	26.9	1.3	3.8	1.0	5.5	1.7	-	-	-	-	-	-	-
	2	21.6	32.4	3.7	1.8	26.0	1.1	0.6	-	2.3	5.9	3.2	-	1.6	-	-
	3	22.1	31.8	6.2	1.4	23.0	0.7	1.3	-	1.4	6.5	3.8	-	1.8	-	-
	4	20.9	37.9	27.4	1.3	3.5	1.2	5.7	1.6	-	-	0.7	-	-	-	-
C	1	24.0	32.6	5.2	1.3	27.9	0.6	1.4	1.1	-	0.7	5.4	-	-	-	-
	2	24.5	33.0	4.9	1.1	26.9	0.6	1.0	1.0	-	-	4.8	-	-	2.1	-
	3	24.3	32.1	4.5	1.0	28.6	0.5	1.2	2.0	-	0.4	5.5	-	-	-	-
D	1	18.8	41.6	39.7	-	-	-	-	-	-	-	-	-	-	-	-

Fig. SC-1. Acid neutralization capacity (ANC) of fresh and treated B (subfigure a) and F (subfigure b) bottom ashes.

Fig. SC-2. X-ray diffractograms of fresh, aged and treated (heat treatment, moist carbonation and slurry carbonation) B (subfigure a) and F (subfigure b) bottom ashes.

Table SC-2

Mineralogical composition of treated B and F bottom ash samples determined by quantitative X-ray diffraction analysis (in wt.%); there are no indications for the presence of unidentified minerals.

Mineral phase	Chemical formula	B samples			F samples		
		Heat treat.	Moist carb.	Slurry carb.	Heat treat.	Moist carb.	Slurry carb.
Calcite	CaCO ₃	8.0	9.8	9.4	2.2	4.8	5.0
Aragonite	CaCO ₃	n/d	n/d	0.7	n/d	n/d	1.2
Vaterite	CaCO ₃	n/d	0.8	0.5	n/d	n/d	n/d
Quartz	SiO ₂	4.8	4.0	6.9	23.7	20.8	21.9
Gypsum	CaSO ₄ ·2H ₂ O	n/d	0.8	0.2	n/d	1.1	0.5
Aluminium	Al	0.1	0.1	0.2	n/d	n/d	n/d
Magnetite ¹	Fe ₃ O ₄	1.4	1.7	2.1	0.4	0.5	0.5
Hematite	Fe ₂ O ₃	0.9	0.9	0.9	1.3	1.3	1.4
Gehlenite	Ca ₂ Al ₂ SiO ₇	3.7	3.3	3.7	0.3	0.3	0.2
Pyroxene ²	XYZ ₂ O ₆	0.8	0.7	1.2	n/d	n/d	n/d
Wüstite	FeO	0.2	0.6	0.6	n/d	n/d	n/d
Wollastonite	CaSiO ₃	1.3	1.5	1.4	0.5	1.2	1.1
Apatite	Ca ₅ (PO ₄) ₃ (Cl,F,OH)	n/d	n/d	n/d	5.5	3.4	2.3
Feldspar_Alkali	(Na,K)Si ₃ AlO ₈	0.6	1.0	0.3	1.6	1.0	1.2
Cristobalite	SiO ₂	0.5	0.5	0.7	0.8	0.6	0.6
Anhydrite	CaSO ₄	0.5	0.4	n/d	3.8	3.5	3.4
Ettringite	Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ ·26(H ₂ O)	n/d	n/d	n/d	n/d	n/d	n/d
Portlandite	Ca(OH) ₂	n/d	n/d	n/d	n/d	n/d	n/d
Others/Amorphous		77.3	74.1	71.2	59.9	61.6	60.6

¹ Or Maghemite (γ-Fe₂O₃) which has a defect spinel structure with a hematite stoichiometry. Magnetite (Fe₃O₄) also has the spinel structure, as well as several other minerals; they cannot always be distinguished unambiguously from the XRD-spectra.

² X : Ca²⁺, Na⁺, Mn²⁺, Fe²⁺, Mg²⁺, Li⁺; Y : Mn²⁺, Fe²⁺, Mg²⁺, Fe³⁺, Al³⁺, Ti⁴⁺; Z : Si⁴⁺, Al³⁺.

n/d : not detected.

Fig. SC-3. BSE images of the polished sections of aged bottom ash sample B. The areas and crosses indicate the positions where EDX-analyses were performed: see Table SC-3 for the analysis results.

Table SC-3

Semi-quantitative SEM-EDX analyses (in wt.%) of aged B bottom ash samples. In Fig. SC-3 the positions (e.g. A1, A2...) where EDX-analyses were performed are indicated.

Analysis point		C	O	Si	Al	Ca	Mg	Na	K	P	S	Cl	Fe	Ti
A	1	18.9	37.9	29.2	0.6	5.8	1.5	5.2	1.0	-	-	-	-	-
B	1	-	3.5	-	96.5	-	-	-	-	-	-	-	-	-
	2	-	44.2	-	47.9	6.9	-	-	-	-	0.9	-	-	-
C	1	21.0	22.8	16.6	0.6	2.7	0.2	2.9	1.3	-	0.5	0.2	31.3	-
	2	19.6	30.2	19.0	1.5	1.4	-	4.1	1.2	0.0	0.9	0.3	21.5	0.2
	3	14.4	27.9	0.4	-	-	-	-	-	-	-	-	57.4	-
D	1	24.7	24.3	33.7	1.0	10.0	1.0	3.4	1.9	-	-	-	-	-
E	1	45.4	36.1	7.2	1.2	3.6	1.9	0.6	0.5	-	3.5	-	-	-
	2	14.2	39.3	19.9	3.0	15.7	1.1	2.0	1.3	0.9	2.6	-	-	-
F	1	13.1	28.3	15.4	1.6	11.5	1.0	1.9	0.6	-	-	-	26.6	-
	2	11.5	25.2	8.9	2.8	6.0	0.6	1.0	0.9	-	-	-	43.1	-

Fig. SC-4. BSE images of the polished sections of aged bottom ash sample F. The areas and crosses indicate the positions where EDX-analyses were performed: see Table SC-4 for the analysis results.

Table SC-4

Semi-quantitative SEM-EDX analyses (in wt.%) of aged F bottom ash samples. In Fig. SC-4 the positions (e.g. A1, A2...) where EDX-analyses were performed are indicated.

Analysis point		C	O	Si	Al	Ca	Mg	Na	K	P	S	Cl	Fe	Ti	Mo	V	Zn
A	1	18.3	33.9	4.2	2.1	27.2	1.2	0.4	-	0.9	6.5	3.1	-	2.4	-	-	-
	2	21.2	39.7	20.6	9.8	-	1.6	3.8	3.3	-	-	-	-	-	-	-	-
B	1	19.3	32.8	4.7	2.0	26.3	1.3	0.6	-	0.8	6.7	2.8	-	2.4	-	0.5	-
	2	19.9	33.1	4.1	1.8	26.1	0.9	0.4	-	0.9	7.9	2.9	-	1.9	-	0.2	-
	3	20.3	38.6	27.6	0.4	5.8	1.9	4.7	0.7		-	-	-	-	-	-	-
	4	21.1	37.5	27.4	0.3	6.4	1.8	2.8	1.0		0.4	0.6	-	-	-	-	0.8
C	1	18.9	34.3	4.0	2.0	26.0	1.2	0.4	-	0.9	7.5	2.3	-	2.5	-	-	-
	2	23.6	40.1	0.6	0.2	35.1	0.4		-	-	-	-	-	-	-	-	-
	3	18.0	38.6	29.5	0.6	5.5	1.7	4.9	1.3	-	-	-	-	-	-	-	-
	4	19.7	33.3	5.2	2.6	25.0	1.2	0.3	-	0.8	7.8	2.7	-	1.4	-	-	-
	5	22.0	39.8	38.3	-	-	-	-	-	-	-	-	-	-	-	-	-
D	1	19.7	39.1	-	-	-	-	-	-	-	1.0	2.9	33.8	-	-	-	-
	2	1.3	3.2	-	-	1.0	-	-	-	-	0.3	-	92.4	-	-	-	-
	3	20.8	35.3	4.2	1.9	24.4	1.0	0.3	-	0.8	7.2	2.5	-	1.8	-	-	-
	4	4.5	10.7	4.4	1.7	53.2	1.1		-	1.8	8.1	4.7	6.6	3.3	-	-	-
	5	19.3	33.4	4.4	1.8	26.2	1.1	0.5	-	0.7	7.3	3.0	-	2.2	-	-	-
	6	19.2	39.1	28.6	0.5	5.9	1.5	4.3	0.9	-	-	-	-	-	-	-	-
F	1	1.8	4.7	-	-	-	-	-	-	-	-	-	93.6	-	-	-	-
	2	11.1	25.7	5.2	3.0	33.8	1.0	0.1	-	-	7.5	3.9	5.5	3.3	-	-	-