

Extraction of heavy metals from municipal solid waste incinerator (MSWI) bottom ash with organic solutions

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Abstract

Municipal solid waste incinerator (MSWI) bottom ash often cannot be recycled as construction material in Flanders, because leaching of Cu exceeds the limit value of 0.5 mg/kg. Leaching of other components such as Mo and Sb is critical as well, but limit values for these elements are to date only informal. A treatment technique was investigated to lower pollutant leaching: extraction with solutions of organic complexants to remove Cu. Six different solutions were used, of which washing with citric acid and ammonium citrate decreases Cu leaching to below the limit value. Extraction was then performed with different concentrations of ammonium citrate. Subsequent washing of the extracted material with distilled water appears to be vital to remove all residual ammonium citrate. Extraction with a 0.2 M solution of ammonium citrate followed by three washing steps decreases metal leaching to below the limit values.

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1. Introduction

Recycling of waste material is a topic of growing importance in the field of waste management. Bottom ash, originating in the grate furnace of a municipal solid waste incinerator (MSWI), is an example of a material with a high recycling potential. It can replace the sand or gravel fraction in concrete bricks or can be used as such in foundations [1,2]. For bottom ash to be recycled, the material must comply with strict regulations, consisting of civil-technical (strength, grain size distribution,) and environmental requirements. While the former requirements do not seem to be a problem for bottom ash, the latter are. Worldwide, leaching of heavy metals such as Cu, Pb and Zn is reported to exceed the local limit values substantially, to an extent depending on the incineration process parameters and the local limit values [3].

In Flanders MSWI bottom ash can be recycled when limit values for the total element concentration and leaching are not exceeded (Table 1). The limit values for total concentration are only indicative. Besides eight regulated inorganic pollutants (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn), seven others are up to now not

regulated, but informal limit values have been suggested. Civil-technical requirements are regulated as well, but depend on the specific recycling option. For MSWI bottom ash, Cu leaching is the main problem in Flanders [4], with a total content ranging from 1 to 10 g/kg dry matter (DM) and leaching consistently exceeding the Flemish leaching limit value of 0.5 mg/kg DM by a factor of 1 to as high as 200, depending on the MSWI and the bottom ash fraction.

Leaching of metals from bottom ash and the reduction of its importance has been the subject of several investigations. Various techniques have been proposed ranging from physical ones such as sieving and (dia-) magnetic separation to chemical ones such as washing and carbonation [2]. When focusing on Cu leaching, a predominant mechanism is the formation of highly soluble organo-copper complexes. Martell [5] states that the stability of complexes of some common divalent metal ions is predicted to follow the order; $Cu > Ni > Pb > Co > Zn > Cd > Fe > Mn > Mg$, this order being independent of the nature of the ligands. Bottom ash typically has a TOC of 1–4% [1,6]. Although the exact speciation is still under investigation, it is clear that high organic carbon content is correlated with high Cu leaching [7–9]. A treatment method taking advantage of this mechanism, especially for Cu, is the extraction of MSWI bottom ash with solutions of organic complexants. Extraction with organic complexants increases leaching, thereby

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Table 1
Flemish limit values^a (mg/kg dry matter, DM) for recycling of granular material in construction applications

	Total content ^b	Leaching
Regulated metals		
As	250	0.8
Cd	10	0.03
Cu	375	0.5
Cr	1250	0.5
Hg	5	0.02
Ni	250	0.75
Pb	1250	1.3
Zn	1250	2.8
Non-regulated metals		
Ba	7500	1.6
Mo	185	0.2
Sb	50	0.1
Se	5	0.04
V	1250	0.8

^a Flemish regulations of December 17, 1997 (revised in 2004) on waste prevention and management [Vlaams reglement van 17 december 1997 (volledig herzien in 2004) inzake afvalvoorkoming en -beheer, VLAREA].

^b Indicative values.

(partly) removing the Cu fraction that otherwise forms organo-copper complexes with the organic matter in the bottom ash. The removed Cu cannot be released in a subsequent leaching step anymore.

Extraction of heavy metals with organic complexants has been extensively used to clean contaminated soils [10–15]. Typical extracting agents include ethylenediaminetetra-acetic acid (EDTA), diethylenetriaminepenta-acetic acid (DTPA) and nitrilotriacetic acid (NTA), of which the first is the most studied. Fewer reports are available for waste materials. Nugteren et al. [16] report promising results for coal fly ash with EDTA, citric acid and oxalic acid. An extraction solution to solid ratio of five was recommended. Kinoshita et al. [17] used oxalic acid and citric acid to remove heavy metals from bottom and fly ash from automobile tire combustion. Citric acid gave the best results. Pedersen et al. [18,19] removed heavy metals from MSWI fly ash by electrodialysis with ammonium citrate and sodium citrate as assisting agents.

No extraction experiments have yet been applied to MSWI bottom ash, although this residue represents the largest fraction of MSWI solid waste. In addition it is the residue with the highest potential for recycling in construction applications. Therefore, this paper focuses on the removal of heavy metals from MSWI bottom ash. A wide range of inorganic pollutants has been assessed in this paper, including oxyanion-forming elements such as Mo, Sb and Se. They have recently received more attention since they are included in the new European Landfill Directive [4].

2. Materials and methods

2.1. Bottom ash and leaching test

The bottom ash studied in this paper already underwent an on-site treatment after quenching. The material went through

several wet-sieving steps to separate the light organic fraction and the fraction larger than 50 mm from the main stream, and to send these back into the incinerator. The main stream again went through a wet-sieving process to produce three fractions: 0–2 mm, 2–6 mm and 6–50 mm. Magnets removed ferrous material from the granulate fractions of 2–6 mm and 6–50 mm. The Eddy current technique was used to separate non-ferrous material from the 6–50 mm granulate fraction. The smallest fraction was separated in a sand fraction (0.1–2 mm) and a sludge fraction (0–0.1 mm). More details on the on-site treatment can be found elsewhere [20]. It is mainly the sand fraction that is studied in this investigation because of its non-compliance with the Flemish environmental limit values, whereas the two granulate fractions comply in general with these limit values. Two batches of material were collected at different dates. Immediately after collection, batch 1, consisting of raw unsieved (i.e. no on-site treatment) bottom ash, was dried in an oven at 40 °C for six days, batch 2 (sand fraction) was dried at 50 °C for nine days. The dried samples were stored in closed buckets to slow down transformation reactions.

Leaching of metals from the granular material was determined using the EN 12457-2 test (batch extraction with distilled water for 24 h with an L/S = 10) and measuring the resulting liquid sample for its metal content using a VG PlasmaQuad PQ-2 Plus ICP-mass spectrometer.

2.2. Extraction with solutions of organic complexants

Extraction tests were performed initially on the raw unsieved bottom ash (batch 1) to get an overview of the potential of extraction for the improvement of bottom ash as a whole. Before the extraction tests, ferrous material was removed with a hand magnet and the bottom ash was milled to particles smaller than 4 mm. Acetic acid, ammonium citrate ((NH₄)₂-citrate), citric acid, oxalic acid, sodium EDTA (Na₂-EDTA), and tartaric acid were used in extracting solutions. The procedure was as follows: dry material is extracted for 1 h with a 0.1 M solution of the complexing agent at L/S = 5; the slurry is filtered over a membrane filter (0.45 μm) and the residue on the filter is washed with distilled water for 1 h at L/S = 5 in order to remove remaining complexing reagent; after filtration the residue is leached, filtered and leached again.

The investigation then focused on ammonium citrate as complexing agent. Extraction tests were performed on the sand fraction of bottom ash from batch 2 because this fraction remains unrecycled to this date. First the material was extracted with an ammonium citrate solution (1 h at L/S = 5). After extraction, the slurry was filtered over a membrane filter (0.45 μm). Then the residue on the filter was washed with distilled water (1 h at L/S = 5) in order to remove remaining organic complexant. Finally the suspensions were filtered (0.45 μm) and the resulting residue was leached. The optimal sequence was investigated by varying the concentration of ammonium citrate, the number of extraction steps and the number of washing steps.

Table 2

Amounts of inorganic pollutants released (mg/kg DM) for the raw bottom ash and sand fraction, together with the Flemish limit values for recycling of granular material in construction applications

	Flemish leaching limit value	Batch 1 (unsieved bottom ash)	Batch 2 (0–2 mm sand fraction of the bottom ash)
As	0.8	<0.01	<0.01
Cd	0.03	<0.01	0.25
Cu	0.5	13.4	59.3
Cr	0.5	0.19	2.8
Hg	0.02	n.a.	n.a.
Ni	0.75	0.15	0.43
Pb	1.3	0.77	10.5
Zn	2.8	2.6	4.5
Ba	1.6	5.4	13.5
Mo	0.2	0.70	1.0
Sb	0.1	0.10	0.29
Se	0.04	0.14	0.11
V	0.8	0.18	0.31

Measured results that exceed the limit values are in bold. n.a. = not analyzed.

3. Results and discussion

3.1. Characterization of leaching properties

Leaching concentrations of pollutants for both batches are shown in Table 2. Batch 1 is unsieved bottom ash and partly consists of inert stony material, whereas batch 2 is the 0–2 mm sand fraction of bottom ash. In this latter batch more reactive material is present relative to batch 1. This is confirmed by the higher leaching concentrations of all measured pollutants. In batch 1 leaching of Cu exceeds the limit value and leaching of Ba, Mo, Sb and Se exceeds the proposed values. In batch 2 leaching of Cd, Cr, Pb and Zn also exceed the limit values besides the elements already listed for batch 1. The values shown in Table 2 are typical for MSWI bottom ash [1].

The most important problem is Cu, with the leaching concentrations exceeding the limit value by a factor of 26 (batch 1) and 118 (batch 2). A technology to improve leaching properties should aim at (a) decreasing Cu leaching to below the limit value, (b) decrease leaching of other regulated pollutants to below the limit value (e.g., Cd, Cr, Pb, and Zn), and (c) decrease leaching of non-regulated pollutants to lower values (e.g., Ba, Mo, Sb, and Se to below their proposed limit value).

3.2. Extraction with six organic complexants

Several solutions of organic complexants were used for extracting inorganic pollutants from the raw bottom ash. The results are shown in Table 3. None of the organic solutions is able to produce a residual material that completely complies with leaching limit values using the given extraction procedure. It appears that using acetic acid or ammonium citrate results in the lowest number of pollutants that exceed their limit value (Cu and Sb) in the second leaching step. Ammonium citrate is the more efficient of the two. Bottom ash treated with citric acid, oxalic acid or sodium EDTA still exceeds the leaching limit values for three pollutants (Cu, Sb, and Se in the case of

citric acid and sodium EDTA; Cu, Mo, and Sb in the case of oxalic acid). Citric acid is the most efficient of the three, and even decreases Cu and Sb leaching more than acetic acid. Tartaric acid appears to be the least efficient of the investigated organic solutions: leaching of six inorganic pollutants exceeds their corresponding limit values. From these results the following order can be defined with respect to improvement of leaching properties: ammonium citrate > citric acid > acetic acid > oxalic acid = sodium EDTA > tartaric acid.

Removal of a large amount of pollutant does not necessarily imply an important decrease of subsequent leaching. Tartaric acid for example removes more Cu than acetic acid or oxalic acid, but leaching is worse. When all concentrations of the measured pollutants in the extraction and washing step are summed, the following order is found: citric acid (1.6 g/kg) > sodium EDTA (1.1 g/kg) > oxalic acid (0.7 g/kg) > ammonium citrate (0.6 g/kg) > tartaric acid (0.3 g/kg) > acetic acid (0.03 g/kg). A large removal transfers the environmental problem to a liquid waste that needs to be treated. Although citric acid produces promising leaching results, the contamination of the extract reduces its applicability in industry.

The organic solution affects the pH of the bottom ash. In turn, pH affects leaching of pollutants. It could be argued that the extraction treatment is merely removal of pollutants based on their solubility as a function of pH. The example of Cu shows that this thesis is not valid. Cu solubility increases with decreasing pH. Oxalic acid gives the lowest pH at the end of the extraction step (pH 4.7); Cu removal is, however, the second lowest of the six solutions. Sodium EDTA gives the highest pH in the extraction step (pH 9.8), whereas Cu removal is the third highest of the six solutions. A more important parameter than pH is the stability of metal-organic complexes in aqueous solution. Kragten [21] reports a stability sequence as follows: Cu-EDTA (most stable) > Cu-citrate > Cu-oxalate > Cu-tartrate > Cu-acetate (least stable). When this sequence is taken as Cu removal sequence (with Cu-EDTA as largest removal and Cu-acetate as smallest removal), the order is almost identical as in the sequence of cumulative removal in the extraction and washing step (previous paragraph). Only the order of Cu-EDTA and Cu-citrate is reversed, but this could be due to pH interference.

3.3. Improvement of extraction with a solution of ammonium citrate

In the previous paragraph the use of ammonium citrate as extractant was shown to give the highest improvement of leaching properties with relatively small contamination of extracting solution. Therefore, ammonium citrate was chosen to be used in further experiments. Increasing the ammonium citrate concentration from 0.1 to 0.5 M in the extraction step, led to an increase in leaching of all inorganic pollutants (Table 4). In most cases there was also an increase of the concentration in the extracting and washing solutions, indicating that increased removal in the first step of the extraction procedure does not automatically imply a decreased leaching afterwards. This was also noticed in the previous paragraph. Using an ammonium citrate solution

Table 3

Amounts of inorganic pollutants released (mg/kg DM) during extraction (E) of raw bottom ash with six different organic complexants (0.1 M) and subsequent washing (W) step (Release during two subsequent leaching steps is also shown (L1 and L2))

	Acetic acid				Ammonium citrate				Flemish limit value
	E	W	L1	L2	E	W	L1	L2	
pH	7.8	9.2	10.4	10.4	8.6	9.3	10.5	10.4	
As	<0.05	<0.05	<0.01	<0.01	0.83	0.08	<0.01	<0.01	0.8
Cd	0.12	<0.05	<0.01	<0.01	0.30	<0.05	<0.01	<0.01	0.03
Cr	1.6	0.32	<0.01	<0.01	7.2	0.67	0.26	0.1	0.5
Cu	8.7	1.6	4.2	1.3	238	21.4	3.3	0.81	0.5
Ni	0.44	<0.05	<0.01	<0.01	1.8	0.16	<0.01	<0.01	0.75
Pb	0.31	<0.05	<0.01	<0.01	42.2	0.85	<0.01	<0.01	1.3
Zn	9.8	0.14	0.28	0.25	226	2.8	0.34	0.35	2.8
Ba	1.8	0.90	1.6	1.5	9.6	0.62	0.50	<0.01	1.6
Mo	0.66	0.21	0.64	0.16	1.0	0.15	0.33	0.16	0.2
Sb	3.1	1.1	1.7	1.5	9.0	1.5	1.9	1.1	0.1
Se	0.31	<0.05	<0.01	<0.01	0.08	0.18	<0.01	<0.01	0.04
V	0.37	0.10	0.21	0.13	1.3	0.20	0.32	0.28	0.8
	Citric acid				Oxalic acid				Flemish limit value
	E	W	L1	L2	E	W	L1	L2	
pH	5.6	7.5	10.5	10.9	4.8	6.7	9.6	9.9	
As	1.9	0.08	<0.01	0.16	0.16	0.12	0.16	<0.01	0.8
Cd	0.80	1.1	<0.01	<0.01	0.18	<0.05	<0.01	<0.01	0.03
Cr	14.5	0.83	0.55	0.24	2.0	0.05	0.18	<0.01	0.5
Cu	321	14.8	2.3	0.81	11.2	3.0	5.7	1.8	0.5
Ni	5.1	0.40	<0.01	<0.01	4.1	0.34	<0.01	<0.01	0.75
Pb	194	0.76	<0.01	<0.01	0.45	<0.05	<0.01	<0.01	1.3
Zn	1018	3.8	0.10	0.40	634	14.4	0.31	0.15	2.8
Ba	0.48	2.6	1.7	0.90	1.5	0.72	1.1	0.45	1.6
Mo	1.30	0.25	0.32	0.12	0.12	0.10	1.6	0.32	0.2
Sb	16.8	0.68	1.1	0.66	2.8	0.78	1.5	1.4	0.1
Se	<0.05	0.13	0.27	0.14	0.30	0.19	0.37	<0.01	0.04
V	5.50	0.10	0.25	0.20	1.0	0.16	0.25	0.21	0.8
	Sodium EDTA				Tartaric acid				Flemish limit value
	E	W	L1	L2	E	W	L1	L2	
pH	9.8	10.8	11.0	10.4	6.9	7.8	9.7	10.1	
As	1.1	0.13	<0.01	<0.01	0.71	0.13	0.14	<0.01	0.8
Cd	0.49	<0.05	<0.01	<0.01	0.18	<0.05	<0.01	<0.01	0.03
Cr	3.1	0.30	0.1	<0.01	4.9	2.0	2.1	0.86	0.5
Cu	202	15.7	2.9	1.4	83.2	21.0	36.3	23.4	0.5
Ni	0.91	0.07	<0.01	<0.01	2.2	0.60	0.22	0.13	0.75
Pb	534	18.8	1.5	0.39	54.1	14.4	5.5	1.9	1.3
Zn	292	20.8	1.5	0.34	33.8	5.2	13.8	1.5	2.8
Ba	9.6	0.17	0.73	1.6	8.0	3.2	3.9	2.5	1.6
Mo	1.2	0.14	0.21	0.19	0.91	0.27	0.24	0.10	0.2
Sb	9.6	1.6	1.1	0.79	11.1	1.8	1.9	1.0	0.1
Se	0.07	<0.05	<0.01	0.24	0.17	0.12	<0.01	0.44	0.04
V	2.2	0.49	0.23	0.11	2.3	0.24	0.28	0.27	0.8

of 0.2 M or more gave leaching concentrations that were higher than when bottom ash was leached without pre-treatment.

To investigate whether sequential extraction would improve leaching results, an experiment with three extraction steps (0.2 M ammonium citrate) was performed. The results in Table 5 show that although more pollutants are extracted, the pollutant concentrations in the leaching step are higher, except for Cr and Cd.

The previous results show that the more ammonium citrate is used (either in a higher concentration, or in multiple stages), the higher the subsequent leaching becomes. Possibly the washing step is not able to remove the extracting agent from the residue before leaching is applied. Therefore, the use of multiple washing steps was investigated (Table 6). Extensive washing after extraction appears of paramount importance for a sufficient decrease of pollutant leaching. The inclusion of three washing

Table 4
Amounts of inorganic pollutants released (mg/kg DM) in the different solutions obtained during the extraction of the bottom ash sand fraction with varying ammonium citrate concentration

		pH	As	Cd	Cu	Cr	Ni	Pb	Zn	Ba	Mo	Sb	Se	V
Untreated		11.6	<0.01	0.25	59.3	2.8	0.43	10.5	4.5	13.5	1.0	0.29	0.11	0.31
0.1 M	E	9.3	0.81	0.87	360	6.6	1.5	64.5	37.6	9.4	1.2	10.8	0.25	0.94
	W	9.6	0.14	0.13	92	1.7	0.35	5.0	3.6	1.5	0.31	2.7	0.06	0.22
	L	10.7	<0.01	0.09	18	1.0	0.17	0.10	0.27	0.73	0.40	2.3	0.04	0.41
0.2 M	E	8.9	2.3	2.0	528	13.3	2.7	170	127	5.1	1.8	16.8	0.29	2.0
	W	9.3	0.76	0.43	187	4.1	1.1	27.1	39	4.1	0.47	4.3	0.09	0.44
	L	10.0	0.29	0.34	78	1.3	0.42	1.6	1.2	1.4	0.32	3.5	0.07	0.53
0.35 M	E	7.8	4.0	2.7	582	18.4	4.1	390	855	13.1	2.6	23.0	0.38	4.3
	W	8.6	1.2	0.86	239	5.9	1.9	97.7	304	12.7	0.92	8.6	0.12	1.1
	L	9.4	0.63	0.28	156	1.8	1.4	6.5	10.8	3.2	0.44	5.6	0.08	0.46
0.5 M	E	7.4	6.5	2.7	489	18.3	6.6	497	1251	8.7	2.7	29.1	0.40	6.7
	W	8.2	1.3	1.4	457	9.7	7.0	221	602	12.6	1.4	10.7	0.13	1.1
	L	9.1	2.8	0.57	332	3.5	3.3	64.7	282	7.5	0.61	7.6	0.19	0.81
Flemish limit value		0.8	0.03	0.5	0.5	0.75	1.3	2.8	1.6	0.2	0.1	0.04	0.8	

E = extraction step, W = washing step, L = leaching step. Leaching concentrations exceeding the Flemish limit values are indicated in bold.

Table 5
Amounts of inorganic pollutants released (mg/kg DM) in the different solutions obtained during the extraction of the bottom ash sand fraction with three extraction steps (0.2 M ammonium citrate)

	pH	As	Cd	Cr	Cu	Ni	Pb	Zn	Ba	Mo	Sb	Se	V
Untreated	11.6	<0.01	0.25	2.8	59.3	0.43	10.5	4.5	13.5	1.0	0.29	0.11	0.31
E ₁	8.9	2.1	1.7	12.3	515	2.6	182	253	5.3	2.0	17.5	0.31	2.2
E ₂	8.5	2.4	1.4	7.9	240	3.9	244	1606	11.2	1.2	14.5	0.14	3.6
E ₃	8.0	1.5	0.81	4.0	82.8	3.4	272	1121	13.1	0.69	10.9	0.069	2.4
W	9.5	0.19	0.15	1.6	326	4.7	24.2	48.0	4.8	0.40	1.92	<0.01	0.07
L	10.0	0.24	0.12	0.29	191	1.6	3.0	16.9	2.0	0.14	3.15	<0.01	0.11
Flemish limit value		0.8	0.03	0.50	0.50	0.75	1.3	2.8	1.6	0.2	0.1	0.04	0.8

E = extraction step, W = washing step, L = leaching step.

Leaching concentrations exceeding the Flemish limit values are indicated in bold.

steps in the extraction procedure allows full compliance of the bottom ash with the Flemish leaching limit values, including the proposed values.

In this improved procedure, 1.2 g of inorganic pollutants per kg of bottom ash (or 0.25 g of pollutants per l of solution) is transferred from the bottom ash to the extracting and washing solutions. In addition, a large amount of wastewater is generated: 20 l for each kg of bottom ash treated. Multiple use of extracting or washing solutions has not been investigated but could

lower the production of wastewater and subsequent treatment cost.

The time of extraction was kept constant at 1 h throughout the investigation. Nugteren et al. [16] conclude that, in the case of coal fly ash, a reaction time of 5–15 min should prove long enough to obtain maximum extraction for most heavy metals. This has not been investigated further here, but it is anticipated that the extraction of coarse particles (e.g. bottom ash) might require longer extraction times than fine materials such as fly ash.

Table 6
Amounts of inorganic pollutants released (mg/kg DM) in the different solutions obtained during the extraction of the bottom ash sand fraction with one extraction step (0.2 M ammonium citrate) and three washing steps

	pH	As	Cd	Cr	Cu	Ni	Pb	Zn	Ba	Mo	Sb	Se	V
Untreated	11.6	<0.01	0.25	2.8	59.3	0.43	10.5	4.5	13.5	1.0	0.29	0.11	0.31
E	8.8	2.3	2.0	13.3	528	2.7	170	127	5.1	1.8	16.8	0.3	2.0
W ₁	9.3	0.1	0.43	4.1	187	1.1	27.1	38.6	4.1	0.5	4.3	0.1	0.4
W ₂	9.6	<0.01	0.68	2.6	70.0	0.83	3.2	2.3	2.7	2.0	0.9	<0.01	0.2
W ₃	10.0	<0.01	0.23	1.0	0.70	0.55	1.2	1.1	0.87	<0.01	0.2	<0.01	<0.01
L	10.9	<0.01	<0.01	0.23	0.37	<0.01	0.67	0.22	<0.01	<0.01	<0.01	<0.01	<0.01
Flemish limit value		0.8	0.03	0.50	0.50	0.75	1.3	2.8	1.6	0.2	0.1	0.04	0.8

E = extraction step, W = washing step, L = leaching step.

4. Conclusions

In order to reuse MSWI bottom ash as granular construction material in Flanders, treatment is necessary to lower leaching of several pollutants, of which Cu is the most important.

A treatment method was investigated where bottom ash was extracted with an organic solution. Six complexants were investigated: acetic acid, ammonium citrate, citric acid, oxalic acid, sodium EDTA and tartaric acid. Ammonium citrate appeared the most promising agent. Therefore, the procedure was further improved with this complexant. It was shown that washing of the residue after the extraction step was important to remove excess complexant from the residue. The improved procedure consists of one extraction step with a 0.2 M ammonium citrate solution at L/S = 5 for 1 h and three washing steps with distilled water at L/S = 5 for 1 h each. The residue complies with all leaching limit values, including the informally suggested ones, for reuse as granular construction material.

Although this technique gives satisfying results in laboratory, it remains to be investigated if this can be applied in a practical installation. The amount of steps to be performed (one extraction step and three washing steps), the use of expensive reagents (0.2 M ammonium citrate) and the production of wastewater (20 l/kg of bottom ash) are obvious drawbacks.

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