



Controlled combustion tests and bottom ash analysis using household waste with varying composition

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ARTICLE INFO

Article history:

Received 10 December 2009

Accepted 12 July 2010

Available online 1 August 2010

ABSTRACT

The influence of the co-combustion of household waste with either sewage sludge, shredder fluff, electronic and electrical waste (WEEE) or PVC on the bottom ash quality and content was investigated under controlled laboratory conditions using a pot furnace. This laboratory approach avoids the interpretation problems related to large variations in input waste composition and combustion conditions that are observed in large scale MSW incinerators. The data for metals content, transfer coefficients and leaching values are presented relative to data for a base household waste composition that did not contain any of the added special wastes. The small WEEE invited direct measurement of precious metals content in the ashes, where measurement accuracy is facilitated by using only mobile phone scrap for small WEEE. The analyses were carried out for different particle size ranges that are of relevance to the recyclability of metals and minerals in the ashes. Positive correlations were found between elements content of the input waste and the bottom ashes, and also between increased levels of Cl, Mo and Cu in the input waste and their leaching in the bottom ashes. These correlations indicate that addition of PVC, small WEEE and shredder fluff in input waste can have a negative influence on the quality of the bottom ashes. Enrichment of Au and Ag occurred in the fractions between 0.15 and 6 mm. The precious metals content represents an economically interesting intrinsic value, even when the observed peak values are properly averaged over a larger volume of ashes. Overall, it has been shown that changes in quality and content of bottom ashes may be traced back to the varied input waste composition.

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1. Introduction

Recycling of bottom ashes from household waste incinerators holds significant environmental and economical advantages. For example conservation of landfill space and minimization of environmental impact (Wile, 1996), and it provides a secondary source of raw materials while reducing CO₂ production (e.g. by replacing primary aluminium). Studies from several European countries indicate that bottom ash can be recycled as a building material fraction (Izquierdo, 2001; Forteza and Far, 2004; Bertolini et al., 2004). For that purpose some innovative technologies are treating the ashes to obtain a new resource for high-grade building materials, such as concrete tiles and prefabricated building parts (Zwahr, 2004; Rübner et al., 2008). The technical possibilities and societal acceptance of recycled bottom ash depends on its environmental quality, e.g. the toxicity and leaching. Especially leaching of salts (chlorides,

sulphates) and heavy metals (copper, zinc, lead) may limit the application of recycled bottom ash materials (Sabbas et al., 2003; Arickx et al., 2007). Leaching can be reduced by treating bottom ash through physical separation (Muchova and Rem, 2006), chemical purification (van Gerven et al., 2005), or ageing treatment (Meima and Comans, 1999). All these methods have limitations in terms of effectiveness and costs.

The main input stream of municipal solid waste incinerators (MSWI) is household waste but various types of hazardous and industrial waste may also be found, depending on the local policies for waste collection and disposal. Increasing amounts of sewage sludge (SS) or shredder fluff (SF) are co-incinerated with household waste because it offers three distinct advantages: volume reduction, destruction of organic micro-pollutants and pathogens, and energy recovery (Werther and Ogada, 1999; Shuji and Yuichiro, 1999). The SS and SF may have a more severe environmental impact due to their heavy metals content. While SS and SF may be co-incinerated on purpose, electronic and electrical waste (WEEE) and PVC appear to be an unavoidable part of household waste. The reason these are incinerated is that thorough quality inspection of input household waste is usually considered too expensive

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for MSWI. Instead, inspection occurs mostly visually and superficially through selective inspections of incoming garbage trucks. Nevertheless, PVC has been defined as an environmental risk when incinerated (Bernard et al., 2000), while WEEE is defined as outright hazardous (Final Report of UNU of WEEE, 2008).

On the other hand, WEEE is not only hazardous but it also contains precious metals. Provided the amount of WEEE in input household waste is large enough it may be economically viable to liberate precious metals from bottom ashes with similar methods as used for WEEE streams (Cui and Zhang, 2008). According to the EU directive for WEEE (Directive 2002/96/EC, 2003), mobile phones are a typical part of category III WEEE and should be recycled separately. Nevertheless, many small WEEE apparatus are discarded in household waste. A German study showed that household waste contains 1.4–2.8% of small WEEE (shavers, hair-dryers, mobile phones, etc.) (Janz and Bilitewski, 2007). This finding is consistent with UK questionnaires in which 23–60% of UK residents claimed they sometimes throw small WEEE in the waste bin (Darby and Obara, 2005), and WEEE (all categories) therefore makes up 4% of UK household waste. The precious metals in bottom ash from small WEEE should be seen apart from metallic particle sources, such as pieces of jewellery. The latter may be liberated by physical separation techniques from coarser fractions. The WEEE precious metals must mostly be liberated by chemical or metallurgical techniques from the finer fractions, where they could still be fused or adhered to carrier materials such as plastic packaging or the silicon wafer material of electronic circuit board components.

This study aims to investigate what the influence of added special wastes could be on bottom ash quality and content, and if that influence may be traced back to the specific input. This is achieved by conducting controlled laboratory tests and comparing concentration and leaching measurements to a base line provided by samples of only base household waste. The added intrinsic economic value due to co-combustion of small WEEE is a different kind of impact, but one that could motivate a higher degree of recycling of bottom ashes. This economic impact was investigated by a direct measurement of the precious metals content of the ashes. In Section 2 the test facility, samples, incinerator and analyses methods are introduced. In Section 3 the bottom ash measurements are discussed for four different particle ranges in terms of transfer coefficients, concentrations, leaching, heavy metals and precious metals content. Section 4 contains conclusions.

2. Materials and methods

2.1. Lab-scale incineration versus large scale MSWI

The input base waste composition in Table 1 and the combustion conditions in the pot furnace tests in Table 2 were tuned to average values for a full-scale grate-type MSWI in the Netherlands, more specifically the AEB and TWENCE facilities. There are two noticeable deviations from the average MSWI input waste composition. First, the average contents of WEEE and PVC are omitted in the base waste to get a clear reading of their influence on the bottom ashes as a special waste. Second, the base waste had an average calorific value (CV) of 15.6 MJ/kg, which was higher than average for MSWI in the Netherlands (9.5 MJ/kg). This was caused mainly by a 9% lower average moisture content and a higher relative newspaper and dry beans content that ensured continuous combustion in the small scale laboratory incinerator. The average sample moisture content was 11%, while the moisture content of input waste of MSWI in the Netherlands varies roughly 10–30%.

Nevertheless, to counteract the high CV the important combustion parameters in the tests are kept similar to real MSWI, which

may be inferred from Table 2 that shows the main combustion parameters in the conducted tests and for a grate-type MSWI. Generally MSWI deal with large variations in input waste composition, while they also show large variations in combustion conditions. For example, the combustion temperatures in the fuel bed typically vary between 750 and 950 °C, the air factors vary from 1.5 to 2.0, while the combustion time may vary between 30 and 75 min. The pot furnace and synthetic input waste samples prevents these large variations and therefore give much better reproducibility between tests. To that effect the pot furnace approximates only average thermal conditions in a real MSWI. Such control and reproducibility in a laboratory test are contrary to full scale studies (Hyks and Astrup, 2009). In a MSWI it is quite difficult to detect influences of specific input waste variations on bottom ash quality and content, especially if the latter parameters are related to averages from quite large volumes of ashes.

A limitation of the pot furnace is that its small size (10 cm diameter and 130 cm height) does not allow incineration tests to be conducted on true MSWI input particles scale. This may have had some influence on the partitioning of the bottom ashes, although the relation between scale and partitioning is not clear. Another factor in a MSWI that might affect combustion is the movement and possible turning-over effect of burning material on the moving grate. The only movement of burning materials that the pot furnace allows is due to the gradual collapse of the waste stack as it burns from top to bottom. These differences are deemed acceptable in that they will not affect the study into the possible effects of input waste variations on the bottom ashes. However, they were believed to strongly affect the flue gas emissions, which is why those emission readings are not taken into account in this work. Overall one should be careful when extrapolating results from the lab-scale tests to real MSWI (van Kessel et al., 2004).

2.2. Input waste samples

The base waste samples were composed of typical components found in household waste in Western Europe (Eurostat, 2003). Table 1 shows the input base waste contained organics, paper, sand, textile, ceramics, glass, wood, iron, building materials and plastics (not PVC). The added special wastes were amounts of mobile phone scrap, SF, SS, and pure PVC. The used SS had 65% moisture content and was taken from the treatment of municipal waste water in Rotterdam, the Netherlands. The SF was formed by the residues from a mechanical polishing process of hand tool manufacturing. Large particles and components with a size bigger than 10 cm in the input waste were handled through cutting and crushing to make it fit into the pot furnace. The test matrix is shown in Table 3. The eight targeted elements that defined environmental quality are Cu, Pb, Zn, Mn, Mo, Cr, S and Cl. These were selected because: (1) these elements are found in relatively high concentrations in the selected special wastes, for example 46–50% of Cl and about 4400–5600 µg/g of Pb in PVC; (2) the targeted metals (except Zn) are expected to partition in higher concentrations in bottom ash than in other residues like fly ash and flue gas due to their physical-chemical properties such as low vapour pressure; (3) they may hold a specific risk to the environment.

The added 2% mobile phones and 5% PVC represent occurring peaks in the composition of MSW waste (Bernard et al., 2000; Toner, 2002). The target elements content of the selected mobile phones are representative for small WEEE category III, except for the contents of Zn, Mo and precious metals that are somewhat higher (Final Report of UNU of WEEE, 2008; Report Produced for DERFA, 2004). The 2% mobile phone content also allows very accurate measurement of the content of precious metals (Ag, Au) in the different size fractions, as it puts their content well above the detection level of the INAA method (Hoffman, 1989). Samples of

Table 1
Chemical composition of materials in the synthesised waste samples.

Components	Average mass % [*]	Cl (wt.%)	Pb (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Cr (mg/kg)	Mo (mg/kg)	S (wt.%)	Mn (mg/kg)
<i>Base waste</i>									
Newspaper	30	0.04	12	60	21.2	2.76	9.7	0.03	95.93
Organic (beans)	30	0.017	1.8	18	38	22.4	0.0068	0.38	18.4
Iron	3	0.017	346	105.8	162	100	200	0	0.4113
Wood	3	0.078	0.52	0.84	8.5	0	0.9	0	78.65
Textile	3	0.07	1.05	0.85	5.45	0.091	440	5.07	0.61
Sand	5	0.034	13	16.5	41.8	289	80	0.02	54
Ceramics	3	0.014	53.4	31.9	110.5	4837	78	0.02	13.5
Glass	3	0.044	20.3	11	70.5	124	47	0.1	0
Building Materials	5	0.046	8.9	18.8	10	29	100	24.8	23
Plastics	5	15	167	13	16	2.3	0.05	0.1	14
<i>Special waste</i>									
SF	2	0.38	2200	5009	11940	700	160	0.67	3080
SS	4	0.08	1001	456.8	1991	43	130	1.9	719
Mobile phone	2	0.76	1060	69600	22800	1400	200	0.5	4700
PVC	5	46	5566	11.8	15.8	0	0	0	27

^{*} The percentage is relative to the maximize sample size of 3500 g.

Table 2
Combustion conditions for a typical MSWI (Netherlands) and laboratory-scale pot furnace.

	MSWI	Pot furnace
Bed Temperature (bottom) (°C)	850	–
Bed Temperature (top) (°C)	840	850
Air flow (m ³ /h) (scaled to 10 cm diameter area)	12	12
Air ratio excess	1.2	–
Combustion time (min)	50	50
Flue gas (°C)	600	–

Table 3
Test matrix.

	Samples of synthetic waste [*]	Replicates of combustions tests
Base line	Base waste	3
Added special waste	Base waste + 5% PVC	3
	Base waste + 2% SF	3
	Base waste + 2% WEEE	3
	Base waste + 4% SS	4

^{*} Mass percentage for the added special waste is relative to maximize sample size of 3500 g.

only base waste were burned separately to establish the base line for the measurements.

2.3. Combustion apparatus

Combustion tests were performed in a laboratory-scale pot furnace. The steel furnace was effectively 130 cm high (top-to-grate) and had a 10 cm inside diameter. The steel pipe was insulated by a thermal blanket. The combustion temperature was monitored at regular intervals by 8 thermocouples connected to a temperature controller. A detailed description of the pot furnace is given by van Kessel et al. (2004). The waste feed was supplied via the top of the furnace, while making sure the sample weight and composition was the same for replicated tests. Room temperature combustion air was supplied by a compressor. The complete pot furnace set-up was placed on a balance to measure the decrease in weight during the combustion process. The combustion time was pre-determined for each batch as the time when ignition losses in the furnace residues were less than 3% of the total feed sample weight. All samples were burned under the designed conditions. Each test was replicated to detect and reduce operational errors and material variations between samples.

2.4. Bottom ash samples and analysis methods

After the bottom ashes were removed from the furnace they were quenched and a magnetic separation was carried out first to remove the ferrous metals. The samples were dried further at ambient temperature for three days to reduce the moisture level below 5%, after which they were sieved to produce four size fractions. The experimental procedure for the bottom ash sampling and analysis is depicted in Fig. 1. Organic contents, chemical composition and concentrations of precious metals are investigated in four different particle ranges using chemical analyses and X-ray fluorescence (XRF). The instrumental neutron activation analysis (INAA) was used to accurately measure the precious metals content. Emissions of the ashes were determined from leaching tests, following the EN12457/4 procedure (European Standard Norm). The base waste bottom ash samples, named base bottom ash, provided the base line for the measurements. The target elements are compared by their concentrations and transfer coefficients (TC), where the TC is the ratio of the element content in the bottom ash to that in the input (Baccini and Brunner, 1991).

3. Results and discussion

3.1. Organics content

The organics in the bottom ash were mainly due to incomplete combustion, and to a much smaller degree they may have been due to halogenated species formed from by De novo synthesis. The organic content of the sixteen bottom ash samples varied between 0.9% and 2.4% as presented in Fig. 2. As a reference, the bottom ash organics content for MSWI in the Netherlands varies between 0.9 and 6.6% (Born, 1994).

3.2. Inorganic content and partition about sieve fractions

The average concentrations of the targeted elements in sieve fractions of the bottom ash samples for a special type of waste are compared to the base line in Fig. 3. The average is based on three samples for each type, except for added SS for which four samples were used. The homogenization procedure used in preparing the waste samples has proven effective since the standard deviation of the replicated tests is less than 10%, which is small enough to draw conclusions. It should be emphasised that the three base waste samples did not contain any of the special wastes or combustible metal-containing particles like those found in packaging

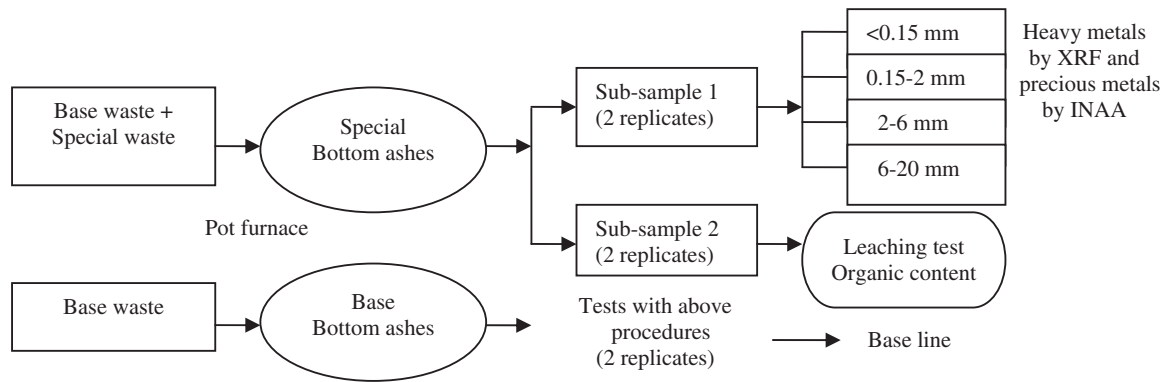


Fig. 1. The experimental procedure for bottom ash sampling and analysis.

materials. The influence of added special waste may be observed as an increase in the concentration of specific elements in certain fractions. However, different special wastes can also increase the concentration of the same element in the same fraction.

Shredder fluff: the presence of 2% SF enriched Cu and Zn by a factor 8–51 in mainly the >6 mm fraction. Mn, Pb and Cl concentrations in <2 mm fractions increased only slightly. **Sewage sludge:** the 4% SS enriched Zn and Pb in the 0.15–2 mm fraction by a factor 4–5. **Mobile phones:** the 2% small WEEE increased the concentrations of Cu, Pb, Zn, Cr and Cl with respect to the base line. The Cu concentration increased most in the >6 mm fraction by a factor of 160, and least in the <0.15 mm fraction by a factor 8. The concentration of Zn and Pb also enriched due to mobile phone scrap and mainly in the >6 mm fraction. It also doubled the Mn concentration in <6 mm fractions and slightly increased the Cr content in the >6 mm fraction. The plastic parts of mobile phone scrap caused up to 5% increase in Cl concentration, and most noticeably in the <2 mm fraction. **PVC:** the added 5% PVC caused more than two times the Cl concentration of the base line in the 0.15–2 mm fraction and more than five times in the >2 mm fractions. The Pb concentration increased by a factor of 3 in the <2 mm fraction, and a factor 5 in the 2–6 mm fraction. The Mo concentration was slightly enhanced in the finest fractions. **Common increases in concentration:** The mobile phone scrap, SF, and SS all caused the concentrations of sulphur to increase between 10% and 50%. The Cr concentration remained mostly unchanged after addition of mobile phone scrap, SF, or SS, with the exception of mobile phone scrap in the >6 mm fraction for which the Cr concentration was increased. However, different special wastes can also increase the concentration of the same element in the same fraction.

The influence of the added special waste may be observed as an increase in the concentration of specific elements in certain fractions. For most target metals the tests confirm the intuitive notion that an increase in metal content of the input leads to a

higher content in the output, except for Zn (Morf et al., 2000). Zinc may form volatile components during combustion and be lost in flue gas, a finding confirmed in large scale testing (Hyks and Astrup, 2009).

3.3. Heavy metals transfer

The transfer behaviour of the targeted heavy metals is expressed as a coefficient.

$$TC(i) = m_{output}^i / M_{input}^i \quad (1)$$

The index is the element type, m_{output}^i is the total mass of the element in the bottom ash, and M_{input}^i is the total mass of the element in the input waste. Based on the data in Fig. 3 the transfer coefficients (TC) for the bottom samples with added small WEEE, SF, SS or PVC were calculated. The average values of partitioning of the heavy metals in the bottom ash are given in Table 4 and depicted in Figs. 4 and 5. Note that the complement in Figs. 4 and 5 ends up in the other residues of the incinerator (fly ash and flue gas).

The TC for heavy metals depends mainly on the physical-chemical properties of those metals and possibly the carrier metals to which they were adhered (Barton et al., 1990; Ho et al., 1994). In waste incineration, Cu is almost entirely enriched in bottom ash owing to its low vaporization properties. Zn, Pb, and Mn may be either equally distributed between bottom ash and fly ash or more distributed into bottom ash. In this study the TCs and partitioning of Cu, Zn, Pb, and Mn from added mobile phones scrap and added SF proved basically similar. For Pb from added SS and PVC and for Zn from added SS the TC's were significantly lower than for other elements. Possibly as a side effect of the high Cl content, the trace Cu and Zn as an additive in PVC could not reliably be retrieved from the bottom ashes.

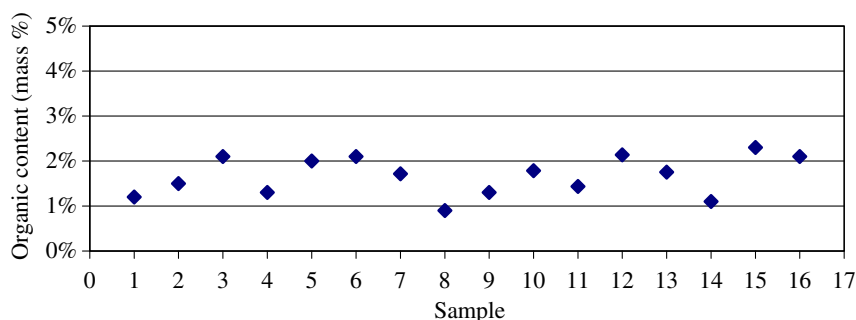


Fig. 2. Organic contents in all bottom ash samples: Base Waste 1–3, BW + PVC 4–6, BW + SF 7–9, BW + WEEE 10–12, BW + SF 13–16.

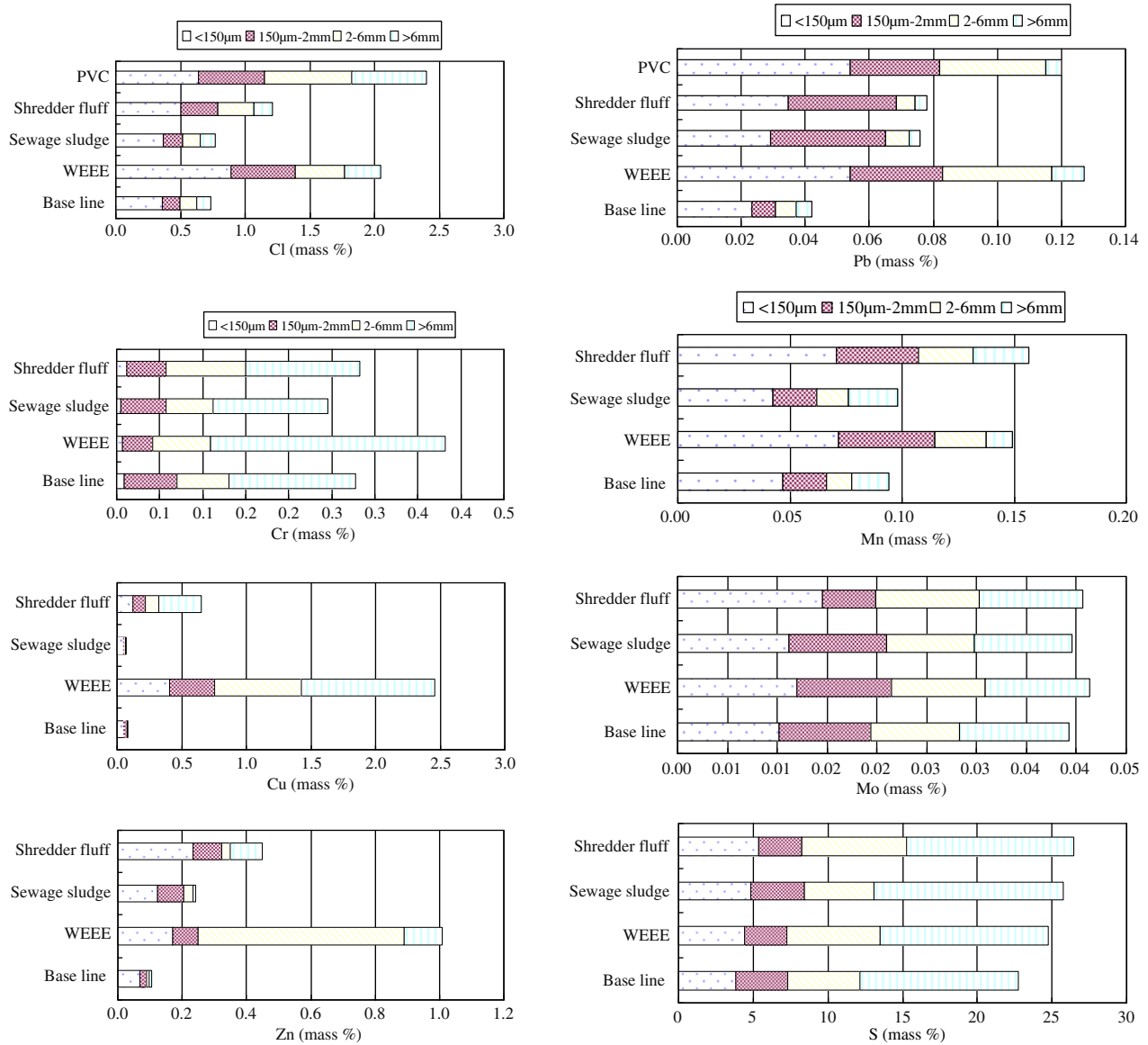


Fig. 3. Average concentration in sieve fractions of the target elements in bottom ash with added special wastes.

Table 4
Transfer co-efficient of selected elements in bottom ash.

Targeted elements	WEEE (wt.%)	SF (wt.%)	SS (wt.%)	PVC (wt.%)
Mn	79–83	70–74	–	–
Cu	90 ± 2	93–96	–	–
Pb	74–78	54–60	25–30	20
Zn	70–75	55–60	18–23	–

The partitioning depends mainly on the mass and size of the carrier metal parts and the specification of metal compounds in the input waste. For Cu, Pb and Zn in the >6 mm fraction for added mobile phones the TC is higher due to the carrier metal and alloys in small WEEE. The heavy metals from SF tend to end up into the fine fractions of the bottom ash. Both the transfer coefficient and the partitioning of heavy metals may be affected by chlorine oxidization, which produces salts that may end up both in the fly ash and in the fine bottom ash fraction (Wang et al., 1999). Chlorides can accumulate in the incinerator if chlorines were amply present in the input waste. The plastic attachments of mobile phone may therefore be the cause of a slight decrease for Cu in Table 4.

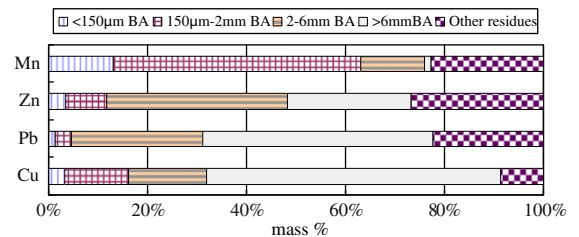


Fig. 4. Transfer co-efficient and partitioning of heavy metals from the waste with added WEEE in bottom ash (BA). The complement ends up in the other incinerator residues such as fly ash and flue gas.

3.4. pH and Leaching

The average pH values of the different bottom ashes were 10.7 for the base samples, 10.9 for the PVC samples, 11.7 for the SS samples, 12.8 for the SF samples, and 12.6 for the WEEE samples. At first sight, the presence of SS, SF or WEEE in base waste may be

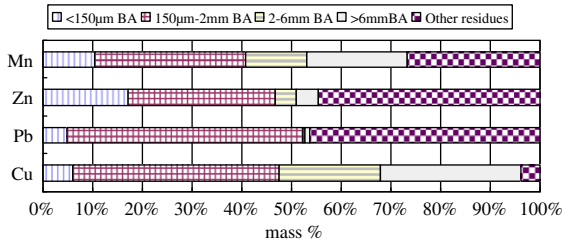


Fig. 5. Transfer co-efficient and partitioning of heavy metals from the waste with added SF in bottom ash (BA). The complement ends up in the other incinerator residues such as fly ash and flue gas.

inferred from an increase in pH of the bottom ashes, but it is possible that the obtained pH depends on the details of the applied combustion procedure. The batch extraction leaching tests are

presented in Fig. 6. There, the left Y-axis shows the total content of the targeted heavy metals in the bottom ash, and the right Y-axis shows the content of the targeted heavy metals in the emission. The levels of Cu and Zn from one of the tests with SF stand out when comparing them with the leaching of base bottom ash. However, two replicate tests show little or no elevated levels for Cu or Zn, but instead show a strong leaching of Mn. This much variation may be indicative of a sampling error and therefore the value was skipped as an outlier. The bottom ashes from the added SS clearly show leaching of both Zn and SO_4^{2-} . With the comparisons of the base lines for Cu and SO_4^{2-} concentrations in the emission of the base bottom ash leaching, the Cu leaching from added SF exceeds its base line by a factor 7, and the SO_4^{2-} leaching from added SS exceeds its base line by a factor 2. The bottom ashes from added mobile phones show strong leaching of Cu, Zn, Mo and Cl. The trend is practically the same for the enrichment with the exception

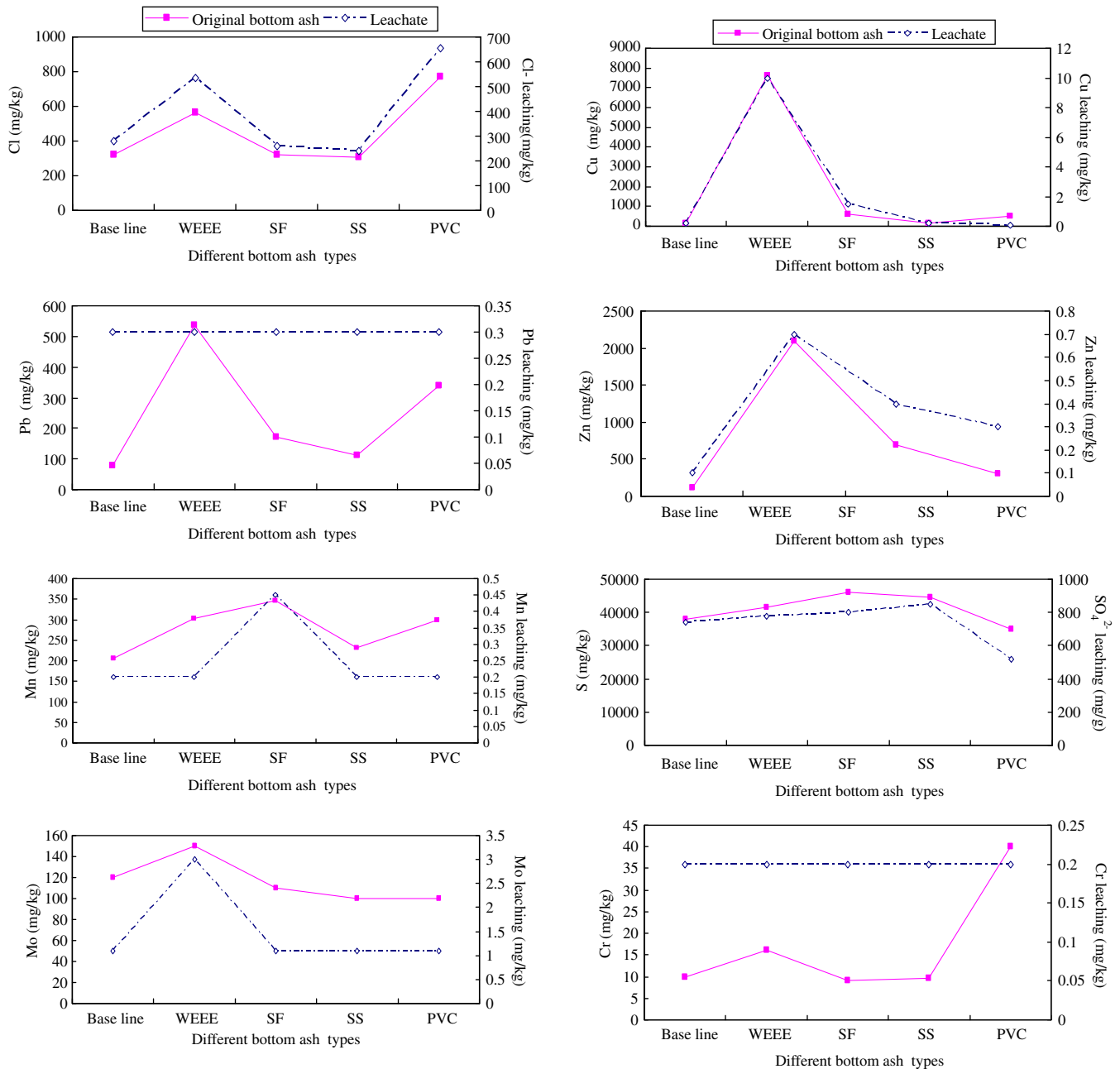


Fig. 6. Influences of the input special wastes on leaching of selected elements in bottom ash (The left Y-axis shows the total content of the targeted heavy metals in the bottom ash, and the right Y-axis shows the content of the targeted heavy metals in the emission).

of Pb, Mn and Cr. The leaching of Cu exceeds the base line of 0.2 mg/kg by a factor of 50, Cl^- exceeds its base line by a factor 2, and Mo is 3 times over its base line of 1 mg/kg measured in emission of the base bottom ash leaching. The added PVC showed increased emission of Cl^- in bottom ash leaching, where the leaching exceeded its base line value by 250%.

The leaching of trace elements may be affected by the pH that is an important parameter in metal solubility and complexation (Stumm and Morgan, 1981). The pH has also been recognised experimentally as an influencing factor in trace element leaching from waste materials and contaminated soils (Dijkstra et al., 2006). On the other hand, experiments also showed that in non-weathered (non-aged) bottom ashes both Cu-leaching and Mo-leaching do not evidently vary with pH for $\text{pH} > 7.5$ (Meima and Comans, 1999), which applies to the results in Fig. 6. It may therefore be expected there is a positive correlation between the increased Cu and Mo concentrations in the bottom ash from the added SF and mobile phone and their leaching values. For Cl^- leaching from bottom ashes with the added PVC and mobile phones it was found that the presence of Cl in the incinerated waste components has a more direct influence on Cl^- leaching.

These results indicate that added special waste can affect the environmental quality of bottom ash. The cause may be directly from their content, or indirectly through their influence on pH and leaching. As far as the concentrations of the other targeted elements in emissions are concerned, their values are too low to provide any clarity as to the possible relation between special wastes and leaching. When referring to the content limits of the Soil Quality Decree and Regulation and the leaching limit of the Building Materials Decree (the final report of monitoring environmental quality of stony construction materials 2003–2006, 2008), the bottom ash with the added WEEE would indicate applicability for reuse as a building material, but not into soil.

3.5. Precious metals partitioning and concentration

It is well known that printed circuit boards, mobile phones, and small WEEE category III in general contain relatively high levels of precious metals such as Ag and Au (DEFRA, 2003; Meskers and Hagelukuken, 2009). The Au and Ag content of WEEE streams have often been characterised, but the partitioning and concentration in the bottom ashes of household waste due to mobile phone scrap is barely investigated. One reason could be that it proved difficult to accurately measure small concentrations. Therefore the instrumental neutron activation analysis (INAA) method is employed, which measurements were optimised for Au that always had the lowest concentration. For these settings, the detection limit was lower than 0.06 mg/kg for Au and lower than 10 mg/kg for Ag. These detection limits were easily reached in the different bottom ash samples when using only mobile phone scrap as small WEEE. Table 5 shows the concentrations of Ag and Au in the different size fractions. The coarsest fraction >6 mm consisted mainly of pieces of metals and plastics that could not be reliably sampled and grinded down for INAA analysis. Since the fines were forcefully

removed from these pieces they were also not expected to contain significant traces of WEEE precious metals. The values in Table 5 are averages from three tests and the concentrations are relative to the total mass of the bottom ash sample. Ag and Au are enriched in the all the <6 mm fractions. If the partitioning of Ag + Au is related to the total mass of Au + Ag in the bottom ashes, 9% ends up in the finest fraction, 49% in the 0.15–2 mm fraction, and 42% in the 2–6 mm fraction. From the total masses in Table 5 the contents ratio can be determined as $\text{Ag}/\text{Au} = 3.3$. This ratio compares quite well to the ratio $\text{Ag}/\text{Au} = 3.9$ determined by measurements on separately collected mobile phones scrap (Cui and Zhang, 2008). The slightly smaller ratio could be indicative of higher losses in Ag than in Au during incineration, but it could also be explained by variations in content between different types of mobile phone. The combined intrinsic economic value of Au + Ag is 450 euro/ton of bottom ashes at present day rates, but these concentrations are due only to added mobile phones that tend to be relatively rich in precious metals. Assuming that concentrations may be scaled down, a conservative factor 15–30 seems appropriate to recover a base line for typical WEEE as encountered in the daily input waste of MSWI. But even down-scaled, the concentration of 0.6–1.3 mg/kg of Au may be economically interesting because its recovery may be combined with recovery of the more abundant non-ferro metals. This means that economical recyclability of WEEE precious metals from bottom ashes cannot be inferred from contents alone, even though a natural resource such as a gold mine may already be economically viable if the ore yields 0.5 mg/kg.

4. Conclusions

The influence of base waste samples with added amounts of shredder fluff, sewage sludge, PVC or small WEEE on the quality and content of the bottom ashes was investigated by comparing concentrations and leaching to a base line. To enable controlled and reproducible tests the incinerations were carried out using a laboratory-scale pot furnace. To mimic the operation of a real MSWI as closely as possible, the main combustion conditions and average input waste composition were tuned to those that are typical for MSWI in western European countries. A limitation of the laboratory furnace approach was that the small scale makes it impossible to mimic a MSWI in every detail.

Positive correlations were found between the target elements contents in the bottom ash and their contents in the input materials, and between the increased levels of Cl, Cu and Mo in the input waste due to the special wastes and their leaching in bottom ashes. Apart from Cl, Mo and Cu, the possible influences of the pH that varied between the different waste samples prevented a clear correlation between the element concentration in the bottom ashes and the degree of leaching. Moreover, the impacts of the special input wastes on the environmental quality of bottom ashes cannot easily be compared on an absolute basis, because besides the pH the leaching may also depend on the specific composition of the different size fractions.

The precious metals content of mobile phone scrap in the input waste could be fully traced back in the bottom ashes using accurate INAA measurements. Results were shown for the four smallest particle ranges to investigate partitioning, which is of relevance to the recyclability of metals and minerals from bottom ashes. The precious metals Au and Ag ended up mostly in the 0.15–2 mm fraction (49%) and the 2–6 mm fraction (42%). The total mass concentrations found were 61.7 mg/kg Ag and 18.9 mg/kg Au. These peak values may be scaled down to a base line for average WEEE in input waste using a factor 15–30, after which they may still represent an interesting intrinsic economic value.

Table 5

INAA measurements of concentration and partitioning of Ag and Au relative to the total mass of the bottom ash sample (na = not available).

Size	Ag ($\mu\text{g}/\text{g}$)	Au ($\mu\text{g}/\text{g}$)
<0.15 mm	6.41 ± 2.74	0.568 ± 1.31
0.15–2 mm	29.6 ± 1.50	9.88 ± 1.23
2–6 mm	25.7 ± 1.48	8.46 ± 1.21
6–20 mm	na	na
Total in bottom ash	61.7 ± 0.989	18.9 ± 0.843

Acknowledgements

This research was funded by the Royal Netherlands Academy of Arts and Sciences, project Innovation Methodologies for Sustainable Waste Management Number 09CDP009, and by Asia-Link, Project Protea Number CN/Asia-link/025(110-744). Both contributions are gratefully acknowledged.

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