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Journal of Hazardous Materials A:64 (1999) 211–222
Journal of Hazardous Materials

Characterization of the bottom ash in municipal solid waste incinerator

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Received 3 August 1998; accepted 15 November 1998

Abstract

The particles with diameter >1 mm present in the bottom ash of Municipal solid waste incinerator (MSWI) were characterized by identifying the main constituent materials. This characterization may be used to evaluate the potential applications of bottom ash and its environmental hazards, and to evaluate the possibilities of recycling its main components. The effectiveness of the voluntary recycling programs of bottom ash can also be assessed. The main components of the bottom ash are glass, magnetic metals, minerals, synthetic ceramics, paramagnetic metals and unburned organic matter. The 4–25 mm size fraction accounts for approximately 50% of the bottom ash weight and comprises mainly glass (>50% of this fraction), synthetic ceramics (>26%) and minerals (>8%), and thus appears to be suitable for reuse as secondary building materials or for glass recycling. Magnetic metals accumulate in the 1–6 mm particle size fraction (6% of this fraction). Heavy metals accumulate in the fraction under 1 mm, unlikely the acid-soluble fraction, which diminishes as particle size diminishes. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Municipal solid waste incineration, MSWI; Bottom ash; Materials; Characterization; Recycling; Reutilization; Particle size distribution

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1. Introduction

Municipal solid waste incineration (MSWI) reduces the volume of waste by about 90% [1,2], and its mass by about 70%. MSWI residues (bottom ash, grate sifting, heat recovery ash, fly ash and air pollution control (APC)), are generated at different points

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PII: S0304-3894(98)00246-5

in the process of MSWI. Approximately 80% of incineration residue is bottom ash. At present, about 17 Mt/yr [3] of bottom ash in the world is produced. This is expected to double in the next ten or fifteen years. Normally, the term 'bottom ash' also includes grate siftings and, depending on the facility design, heat recovery ash.

The incineration process is not the final waste treatment stage. Municipal waste reutilization and disposal options are the focus of debate. In the USA, most MSWI residue currently generated is landfilled, while in some European countries (e.g. Germany, the Netherlands, France and Denmark) about 50% of the stockpiled municipal waste incinerator bottom ash is used as secondary building material, in road construction or as raw material for the ceramic industry inter al. [2–7].

Chemical analyses of MSWI residue, bottom ash, APC residue and combined ash, have often been published [3]. The fact that compositions differ very slightly indicates a relative stability in the proportions of materials in bottom ash, independently of their origin and the particular incineration process. Many leaching tests have been designed by regulatory agencies to characterize trace element mobility and to simulate a field leaching scenario with which the amounts of toxic trace elements available for leaching can be estimated [8].

Bottom ash, which under the regulations of some European countries can be reused as secondary building material or similar, generally contains low concentrations of heavy metals, especially volatile species such as lead, cadmium and zinc. These small amounts of heavy metals are mainly concentrated in the heat recovery ashes and the grate sifting materials, which are collected together with bottom ashes [3], and consist of particle size fractions under 1 mm. However, little research has been conducted on the characterization of the main materials present in bottom ash in particles bigger than 1 mm. The chemical analysis of this particle size fraction gives poor information, which means that a proper evaluation of this materials' reuse and recycling potential cannot be made.

Eighmy et al. [9] described a particle classification from bottom ash but did not take into account this classification for each size distribution of the municipal waste incinerator. This paper reports the most significant results of the characterization of the main materials in the bottom ash particles with diameters between 1 and 25 mm coming from two types of MSWI facilities. This size fraction represents more than 85% of bottom ash [2] and about 68% of the total amount of the solid residue streams (bottom ash and APC residue) produced by a MSWI facility. This characterization can be used to evaluate these materials final disposal, eventual utilization or possible recycling. The amount of glass and other material remaining in bottom ash could be a parameter for evaluating the effectiveness of the municipal voluntary recycling programs.

2. Methods and materials

The bottom ash used in this study came from two MSWI facilities in Catalonia (Spain) which used energy recovery (waste-to-energy, WTE).

Facility A is located in the metropolitan area of Barcelona and began to operate in 1975. In 1996, it handled 302 900 tons (≅ 910 tons/day) of mainly household waste stream with some commercial contributors and produced electric power (118 900 MW h), scrap iron (9000 tons), 77 400 tons of bottom ash and 2500 tons of fly ash collected by electrostatic filters. At present the two residue streams are collected and managed separately. The facility consists of three parallel furnaces, a heat recovery system and an electrostatic precipitator. The three rocking grates of the primary combustion chamber are fed by a large hopper using an electrohydraulic grab. After combustion, bottom ash is dropped into a water-quench tank. After quenching, a magnetic separation is performed with iron and ferrous metals recovery, the material bigger than 250 mm is removed by a trommel and the remaining residue is carried by a drag conveyor to a chute for loading onto disposal trucks.

Facility B is located in the metropolitan area of Tarragona and began to operate in 1991. With two parallel trains of 9.6 tons/h (150 000 tons/yr), it produces 50 000 MW h/yr of electric power and 7000 tons/yr of scrap iron. The feed stream is mainly household waste, with a small input from commercial vendors. The residue is moved across the combustion chamber by rotating rolls. Following combustion, bottom ash (35 000 tons/yr) is water-quenched, then carried by a drag conveyor and magnetic particles are removed. The residue is trommeled to 250 mm for iron and ferrous metals recovery and is finally stored in a bunker before disposal. The flue gases are cooled through heat exchangers with a boiler and sent to a semi-dry scrubber; and particulates are recovered by a fabric filter producing 4000 tons/yr of APC residue. Evacuation, handling and management of bottom ash and APC residue are carried out separately.

In the two facilities, samples were taken from different points of a stockpile of freshly quenched bottom ash between January and March 1997. Samples of about 2 kg were taken every day for 30 days. Afterwards, many representative subsamples of 1 kg, MSWI (a) and MSWI (b), were obtained by the quartering to 1/16 splits procedure.

The particle size distribution of bottom ash was determined by sieving the subsamples as received. The sieving was performed by mechanical shaking with stainless steel mesh screens with openings of standard 1, 2, 4, 6.3, 16 and 25 mm DIN 4188 sieves (1.00, 2.00, 4.00, 6.35, 15.9 and 25.4 mm ASTM standard sieves). After sieving, each fraction, except the under 1-mm fraction, was carefully washed successively with cool water through the sieve in order to separate fine particles adhering to bigger particles. Then, each size fraction was dried at 110°C for 3 h and weighed. Clean particles bigger than 1 mm, in some cases particles were carefully washed with 1 M hydrochloric acid to dissolve the fine alkaline particles adhering to the surface, were separated one by one by observation with optical microscopy and classified as one of the following materials, similar to the classification describes by Eighmy et al. [9]:

2.1. Glass

Glass particles of different colors, some of which had silicate particles adhering to the surface which had been melted at the temperature of combustion (approximately 950°C) inside the burning chamber. Most of these mixed particles had glass as their main constituent and were classified as glass particles. The glass particles of a given size fraction were easily identified after carefully washing the sample for 10 min with an excess of dilute (1 M) hydrochloric acid solution. Unfortunately, since this solution dissolves some of the constituents of the rest of the fractions, it can only by used to determine the mass weight fraction of glass. The main source of glass in the bottom ash are domestic items such as bottles and glasses. Therefore, as glass recycling is increasing, the percentage weight of glass in the bottom ash stream should decrease.

2.2. Synthetic ceramics

Fragments of cement, concrete, pottery, brickbat, porcelain and gypsum. Generally, this type of material in municipal solid waste is due to small-scale domestic building. Particles with a main component melted into the combustion furnace, named slags in metallurgical processes, were classified in this category.

2.3. Minerals

The main components in this category, according to the diffraction pattern obtained by XRD, are quartz (SiO_2), calcium carbonates ($CaCO_3$), lime (CaO) and felspars ($CaO \cdot Al_2O_3 \cdot 2SiO_2$, anorthite). But other materials may be contained in this natural fraction if their percentage weight is lower than 3%, which is the detection limit of the XRD technique: e.g. magnesium carbonate, barite or gypsum. All these inorganic compounds are principal components of agricultural lands, which are unsuitably dumped with organic solid waste. Some phases of these inorganic compounds have been identified by other authors in fly ash, bottom ash and combined ash (see Ref. [1]).

2.4. Paramagnetic metals

Magnetic materials with a particle size fraction lower than 250 mm contained in domestic waste. This fraction was made up mainly of pieces of steel and iron oxidized in the combustion furnace. Magnetite (Fe_3O_4), hematite (Fe_2O_3) and wüstite (FeO) appeared in the X-ray diffraction pattern of this fraction. The identification by XRD of these three phases in the magnetic fraction has also been reported in the literature [1], although only magnetite is paramagnetic.

2.5. Diamagnetic metals

Aluminum, whose melted drops of 2 to 20 mm diameter were found in the respective size fractions. Copper wire of different diameters concentrates randomly in the different size fractions depending on its length and shape. Some spherical particles of copper alloys, melted in the combustion chamber, were found in the smaller size fractions (under 1 mm). Since their specific gravity is around 7 g/cm^3, while the rest of materials have densities of < 3.5 g/cm^3, they can be separated with a pan and identified by optical microscopy and chemical analysis. Over 90% of the weight of this fraction is usually aluminum.

2.6. Unburned organic matter

Carbonaceous semi-burned particles, paper and cardboard carried practically unaltered by the gas flow, fragments of cotton, synthetic fibers and bone fragments. Orange and banana skins are also present since they are able to pass through the combustion chamber almost unaltered.

Each material was weighed and the data used to compose the size and composition distribution diagrams.

A digestion using aqua regia, kept below boiling point, was used to determine the heavy metals available for leaching which were not part of the aluminum-silicate matrix. About 5 to 10 g (in duplicate) of each size fraction, obtained by sieving, washing and drying bottom ash subsamples from Facility B, were digested. Concentration of heavy metals in the leachate (Pb, Zn, Cu, Mn, Sn, Cr, Ni, V and Cd) was determined by a Inductive Coupled Argon Plasma Atomic Emission Spectrometer (ICP-AES). Metal profiles for these metals were created as a function of the particle size in units of milligrams of metal per kilogram of dried bottom ash.

3. Results and discussion

3.1. Particle size distribution

It is surprising to observe that, in all samples of bottom ash from A and B facilities, particles in the 25–250 mm size range were practically non-existent. The trommeled particles over 250 mm were mainly from building or domestic metallic articles. Bottom ash residue comprises mainly ceramic materials, silicates, phosphates, sulfates or carbonates, which are easily broken down by the mechanical system of transport within the furnace or by the effect of the thermal shock. It is possible to find some particles over 25 mm massed together whose matrix, mainly silicates, melted at the combustion temperature inside the furnace. Nevertheless, the bottom ash particles bigger than 250 mm, trommeled and with the magnetic metals removed, weigh $< 3\%$ of the total. The data in Fig. 1 show the accumulative particle size distribution, broken down into the mean particle size for each fraction, and the highest, lowest and average percentage weight values for the two facilities. As can be seen in Fig. 1, up to about 30% of the bottom ash is made up of particles > 6 mm and up to 70% is made up of particles > 3 mm. This fraction over 3 mm is particularly suited to landfilling or being reused as secondary building material or similar, since heavy metals, as will be shown later, are concentrated in the finest fraction. The under 1 mm size fractions of both facilities make up between 15 and 20% of the weight. These fractions are mainly composed of grate siftings, which make up about 1–3% of the weight of the bottom ash [2,4], and boiler ash, which also makes up between 1 and 3% of the weight of the bottom stream. Many of these fine particle stick to the surface of the bigger particles. Comparison of the values obtained for MSWIa and MSWIb subsamples illustrates the similarity between both facilities for particle size fractions under 6 mm: differences of $< 4\%$ in the total average percentage weight were found. However, for particle size fractions bigger than 6 mm, average weight differences $> 7\%$ were found. These differences were probably due to the transportation system inside the furnace. The rotating roll system used in the Facility B furnace tends to produce smaller particles than the rocking grates in Facility

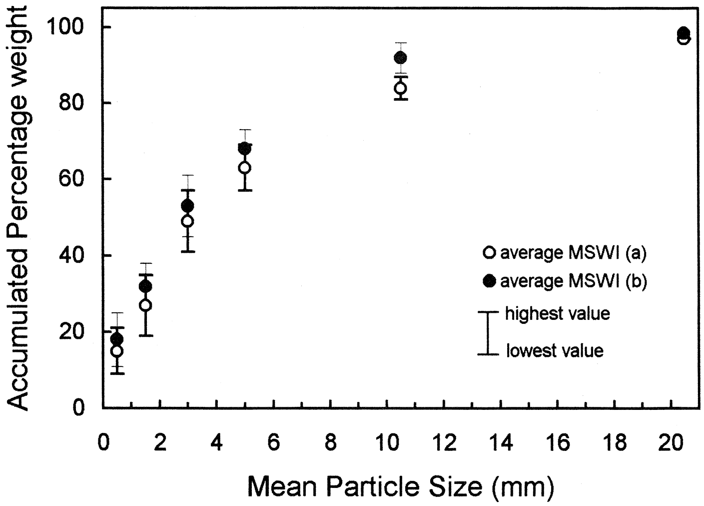

Fig. 1. Accumulated particle size distribution in bottom ash from MSWI (a) and MSWI (b). Averages are shown by bars.

A's combustion chamber. This should be attributed to greater mechanical grinding in the solid transport system inside the furnace. The average bottom ash moisture, as a result of quenching, determined as the weight lost at 110°C, was 21% for Facility A and 26% for Facility B.

The materials in each particle size range are shown in Table 1 for bottom ash samples from the two facilities. All the particles were identified one by one and classified in one of the six component fractions previously described. The material composition of bottom ash > 4 mm, which can be easily sieved and water washed, seems especially suitable for reuse as secondary building materials. More than 50% glass, 8% minerals and 26% synthetic ceramics are the main components of the fraction > 4 mm. The water washing process practically removes the water-soluble fraction and most of the finest particles stuck on the surface, which account for a lot of most hazardous heavy metals. The water used in the sieving and washing process can be further used in the wet or semidry APC systems.

3.2. Distribution of glass in the different size fractions

Glass is the main material in both facilities in each one of the size fractions. Up to 50% of the weight of the bottom ash > 1 mm is glass in Facility A, i.e. 32,500 tons/yr. In Facility B, the proportion of glass is even higher, reaching 60% of the weight of bottom ash > 1 mm, i.e. 17 200 tons/yr. The percentages of glass from bottom ash determined in this study in particle size fractions > 1 mm are lower than those found by other authors who studied combined ashes [1,8]. The difference can be attributed to the voluntary glass recycling programs carried out in the metropolitan areas which the two incinerators cover. The distribution of glass in both facilities is shown in Fig. 2. In both

Table 1
Distribution of materials in MSWI (a) and MSWI (b) bottom ash for different particle size ranges

Particle size range (mm)	Average percentage weight (%)											
	Glass		Magnetic metals		Diamagnetic metals		Synthetic ceramics		Unburned organic matter		Minerals	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
1–2	35	42	13	14	4	3	19	15	2	4	27	22
2–4	45	56	11	13	3	3	17	11	2	3	22	14
4–6	68	75	8	5	2	2	10	7	2	2	10	9
6–16	58	68	5	2	3	2	20	18	1	2	13	8
16–25	45	58	0	0	4	3	51	39	0	0	0	0

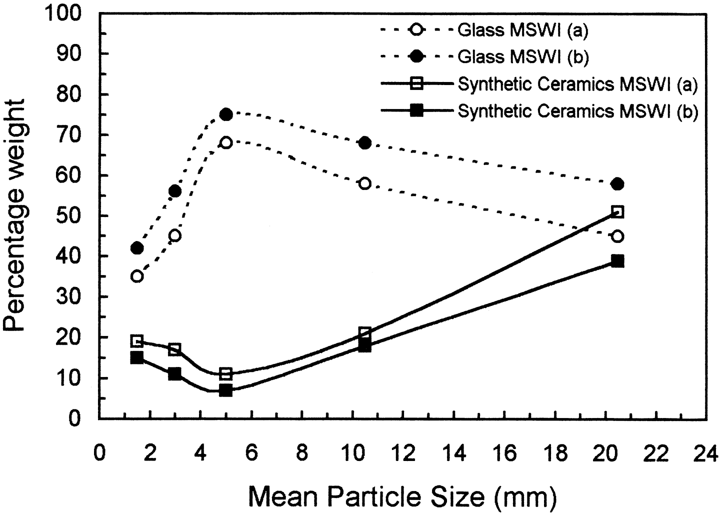

Fig. 2. Percentage weight of glass and synthetic ceramics in bottom ash from MSWI (a) and MSWI (b) as a function of particle size.

cases glass reaches its greatest proportion in 4 to 6 mm fraction, probably due to the breaking action of the mechanical system of solid transport inside the furnace and the effect of the thermal shock.

It is very interesting to see how a material that should not be present in cities with selective collection of urban waste is still the main component in bottom ash from municipal waste incinerators. The glass content in the bottom ash stream can serve as a parameter to evaluate the effectiveness of the voluntary recycling programs, since sieving, washing and classifying can be carried out very quickly and do not require sophisticated characterization techniques. The differences in recycling programs may explain the differences in glass content between the two facilities.

Facility B pulverizes solid particles more than A, but the profile of both distribution curves is similar. Greater pulverization is not associated with a higher concentration of glass in the intermediate fractions, 4 to 16 mm. The break-up of glass can be attributed, in consequence, to the thermal shock in the combustion chamber rather than to mechanical effects.

3.3. Distribution of synthetic ceramics in the different size fractions

The distribution of synthetic ceramics in the two facilities is shown in Fig. 2. The profile distribution curve reaches its minimum in the 4 to 6 mm particle size fraction for both facilities, which reflects the greater resistance of synthetic ceramics to the mechanical and thermal breaking effects of the incineration process. Since synthetic ceramic particles are in fact fragments of building materials they should also not be present since in both cities they are collected in containers separately from domestic urban waste. This again reflects a certain weakness in the selective collection. Since the amount of synthetic ceramics is very easy to determine and in a similar way to glass, this parameter may also be used to determine to what extent people are involved in voluntary recycling. Of the material previously described as being in this size fraction, gypsum is very unusual in particle sizes above 1 mm, probably because it does not survive the transportation system, whereas pottery and porcelain resist breaking and thermal shock better.

3.4. Distribution of magnetic metals in the different size fractions

Magnetic materials are mainly found in the finest fractions, probably due to the characteristics of the magnetic concentrators at the end of the drag conveyor used in the iron and ferrous metals system of recovery from bottom ash in both plants. These concentrators are very effective for particle sizes over 6 mm, but less so for smaller particle sizes (Fig. 3). Water and diamagnetic compounds sticking to the magnetic particles protect small iron and magnetite particles from the external magnetic field. The small differences in the percentage weight of magnetic metals in the two facilities could be due to the effectiveness of the two magnetic separation processes, but are more likely to be because of the presence of more very fine particles in MSWI (b) bottom ash.

The qualitative XRF analysis of magnetic concentrates with particle sizes of < 2 mm identified other nonferrous metals, Mn, Cr, Ti, Cu, Zn, Al, Mg, Si, Sr, Sn, possibly added to special steels or oxides adhering to magnetic particle surfaces. However the XRD of this magnetic fraction identified only ferrous phases, magnetite, wüstite and hematite. These were probably iron oxides generated in the combustion process and released by the mechanical transportation of the solid residue across the combustion furnace.

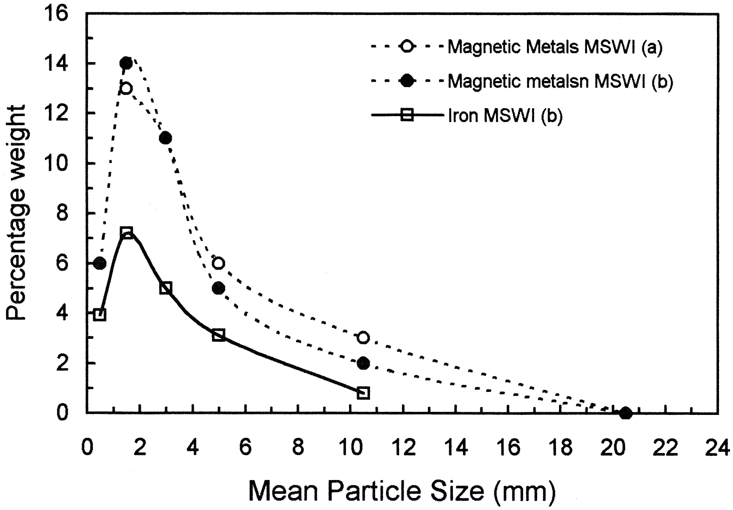

Fig. 3. Percentage weight of magnetic metals in bottom ash from MSWI (a) and MSWI (b) as a function of particle size. Comparison of magnetic and iron concentration from MSWI (b).

Fig. 3 compares magnetic materials and the total iron content obtained by digestion using aqua regia and analyzed by inductive coupled argon plasma (ICP). The profile of both curves is similar and the correlation between these two parameters is clear.

3.5. Distribution of minerals in the different size fractions

Approximately 15% of bottom ash from both facilities were minerals, which had the second highest percentage weight in each size fraction. This material, unlike glass and synthetic ceramics, was mainly found in the smaller size fractions (Table 1). This may be due to the breaking action of the mechanical system of solid transport inside the furnace and the size of the particles dumped, mainly from agricultural lands. Calcium carbonate is the main compound found in this fraction by XRD. It comes mainly from marble used as building material which has been unsuitably dumped. The lime in this fraction, identified by XRD, is the product of calcium carbonate calcination at combustion temperature (above 900°C) in the furnace and it is found over carbonate particles.

3.6. Distribution of diamagnetic metals in the different size fractions

Diamagnetic metals in size fractions lower than 25 mm were very scarce and seemed to be randomly distributed in all size fractions (Table 1). They were also found in the size fraction lower than 1 mm. Although diamagnetic metals were recovered only from the size fractions over 250 mm by bottom ash trommeling, the amount of aluminum and copper present in the untreated fraction in the form of metallic particles, and in consequence potentially recoverable, was considerable. It amounted to more than 2500 tons/yr for the two facilities together. Aluminum was, in practically all cases, more than 90% of the total amount of diamagnetic metals.

3.7. Distribution of unburned organic matter

Unburned organic matter weighed $< 4\%$ in all size fractions and was very similar for both facilities (Table 1). The low percentages show the good combustion at the temperature and remaining time inside both furnaces. Unburned matter seemed to be randomly distributed in all size fractions lower than 16 mm.

3.8. Distribution of heavy metals in the different size fractions

The chemical analysis by other authors [2,4] of bottom ash from many facilities indicated that the finest fraction contributes a significant fraction of the heavy metals. Fig. 4 show the amounts of the most common heavy metals in each size fraction available for leaching from MSWI (b) bottom ash. These are the heavy metals which were not part of the aluminum-silicate matrix and were concentrated in the finest fractions, which may adhere to larger particles. The results show the clear decrease in heavy metal content when as the mean particle size of the fraction increases. The maximum in total lead, copper and tin in the 1–2 mm fraction is due to small metallic particles of copper wire and lead base alloys used for soldering.

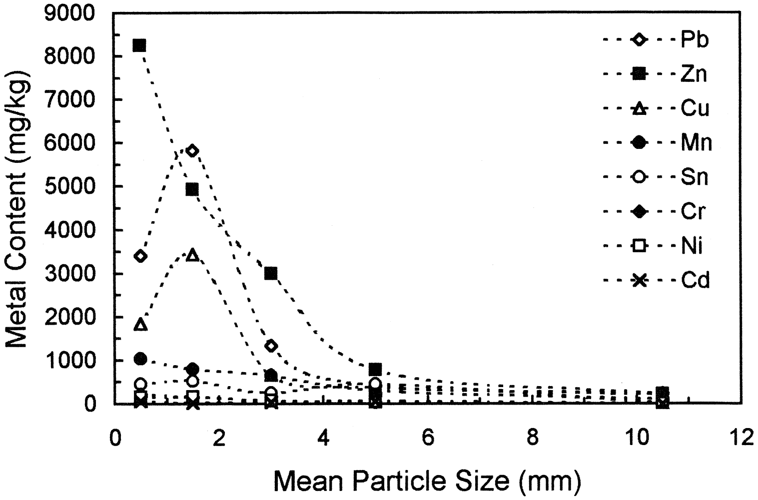

Fig. 4. Lead, zinc, copper, manganese, tin, chromium, nickel and cadmium in bottom ash from MSWI (b) as a function of particle size.

Fig. 5 shows the total heavy metal composition for each particle size fraction. It is surprising that the curve reaches its maximum value in the 1–2 mm fraction, although this value is very similar to the finest fraction. These results show that Pb, Zn and Cu are mainly present in their elemental form and only a small fraction is present as

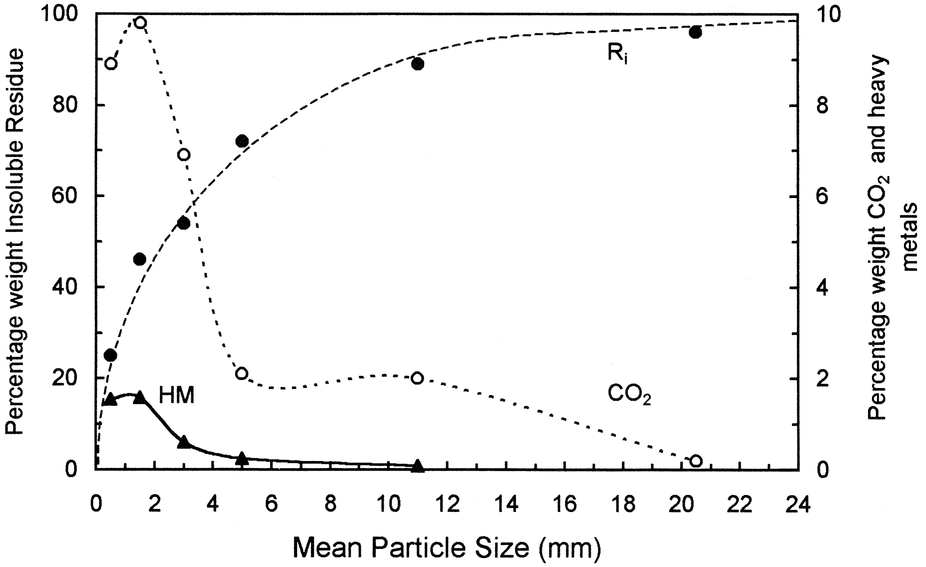

Fig. 5. Percentage weight of CO_2, total metal composition and insoluble residue in bottom ash from MSWI (b) as a function of particle size. The CO_2 is directly related with carbonate contents in bottom ash.

inorganic salts, the majority of which are also not water-soluble in a great range of pH. In fact, the chemical compositions of leachates obtained by DIN 38414-S4 standard test [10] for more than 200 MSWI (b) freshly quenched bottom ash samples show, for lead as well as for zinc, mean values of concentration in the leachate close to 1 mg/l and 0.5 mg/l at $pH > 12.2$.

3.9. Distribution of carbonates and insoluble residue in the different size fractions

The distribution of insoluble residue after leaching with aqua regia in excess for each particle size fraction is plotted in Fig. 5. The percentage of the insoluble residue reflects also the decrease in environmental risks and can be a parameter to assess the behavior of different bottom ash size fractions before their final disposal or utilization. The carbonate content is directly related to the CO_2 evolved in the attack of the sample included in Fig. 5. The profile of this curve is very similar to the profile of the curve for the distribution of minerals, which is consistent with the fact that calcium carbonate is the most abundant compound in this fraction.

Acknowledgements

We would like to thank Mr F. Gatuellas and Mr Ramon Nadal, General Managers of TERSA and SIRUSA , respectively, for their cooperation in financing and supporting this investigation, the Serveis Científico-Tècnics of the University of Barcelona and the Fundació Bosch i Gimpera. We also would like to thank Mr Robin Rycroft for linguistic and stylistic advice.

References

[1] C.S. Kirby, J.D. Rimstidt, Mineralogy and surface properties of municipal solid waste ash, Environmental Science and Technology 27 (1993) 652–660.

[2] O. Hjelmar, Disposal strategies for municipal solid waste incineration residues, J. Hazardous Materials 47 (1996) 345–368.

[3] C.C. Wiles, Municipal solid waste combustion ash: state-of-the-knowledge, J. Hazardous Materials 47 (1996) 325–344.

[4] J.A. Stegemann, J. Schneider, B.W. Baetz, K.L. Murphy, Lysimeter washing of MSW incinerator bottom ash, Waste Management and Research 13 (1995) 149–165.

[5] J. Vehlow, Simple, reliable and yet efficient-modern strategies in waste incineration, UTA International 2 (1996) 144–160.

[6] R.A. Rashid, G.C. Frantz, MSW incinerator ash as aggregate in concrete and masonry, J. Materials in Civil Engineering 4 (1992) 353–368.

[7] J.R. Triano, G.C. Frantz, Durability of MSW fly-ash concrete, J. Materials in Civil Engineering 4 (1992) 369–384.

[8] C.S. Kirby, J.D. Rimstidt, Interaction of municipal solid waste with water, Environmental Science and Technology 28 (1994) 443–451.

[9] T.T. Eighmy, J.D. Eusden Jr., K. Marsella, J. Hogan, D. Domingo, J.E. Krzanowski, D. Stämpfli, Particle petrogenesis and speciation of elements in MSW incineration bottom ashes, in: J.J.J.M. Goumans, H.A. Van der Sloot, Th.G. Aalbers (Eds.), Environmental Aspects of Construction with Waste Materials, Studies in Environmental Sciences 60, 1994, Elsevier, Amsterdam, 111–136.

[10] DIN 38414-S4, German Standard Procedure for Water, Wastewater and Sludge Analysis, Sludge and Sediments (Group S), Determination of water Leachability, Benthe-Vertrieb, Berlin and Köln, Germany.