Characteristics of slag produced from incinerated hospital waste

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Abstract

Ash produced from a hospital waste incinerator was treated using a high temperature melting process at 1200 °C. The quality of the produced slag was characterized by X-ray diffraction (XRD), X-ray fluorescence (XRF), leaching tests and sequential chemical extraction of metals. The slag contained large amounts of SiO_2, CaO, Al_2O_3, Sn, Ni, Cu, Ba and B. XRD analysis revealed a moderate crystal structure for the melted slag and identified the main crystals as quartz (SiO_2), kaolinite ($Al_2Si_2O_5(OH)_4$), albite ($NaAlSi_3O_8$) and gibbsite ($Al(OH)_3$). The observed crystal structure assists in preventing the leaching of heavy metals from the slag. Furthermore, the leaching results found the produced slag to comply with disposal limits set by the US EPA. Results from sequential chemical extraction analysis showed that metals in the slag exhibited the strongest preference to be bound to the residual fraction (stable fraction), which is known to have very low leaching characteristics. Melting was found to stabilize heavy metals in hospital waste successfully and therefore it can be an acceptable method for disposal. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Hospital waste; Melting; Slag; Metals fractionation; Metals leachability

1. Introduction

There is increasing concern with disposal of hospital waste, which has exploded recently. From the total composition of hospital wastes, 80% are comparable to domestic solid waste. The remaining 20% include radioactive wastes and pharmaceuticals, hazardous wastes, such as cytotoxic agents used in chemotherapy, chemical wastes, infectious wastes, contaminated sharps, anatomical wastes and pathological wastes [1]. Disposal of these wastes, which have enormous potential to cause irreversible health damage, is one of the main environmental

concerns to local authorities. Several types of treatment and disposal processes have been applied to hospital waste. However, incineration has been identified as the best option for the disposal of hospital wastes in many areas [2]. Incineration produces ash, which is enriched with heavy metals and can leach into soil and ground water. Lombardi et al. [3] reported the excess leaching of Cd, Zn and Pb from incinerated hospital waste ash. Studies using the US EPA leaching test showed that the concentrations of Cd (1.1 mg/l), Zn (4.2 mg/l) and Pb (9.8 mg/l) exceeded the concentration limits for disposal of theses materials into landfills [3]. Therefore, attempts to stabilize the ash into a stable product, which is environmentally acceptable, has received considerable attention.

The aim of this study is to stabilize the ash produced from incineration of hospital waste by a high temperature melting process and also to quantify the potential hazards associated with the slag produced.

2. Materials and methods

2.1. Characterization of the slag

Ash was obtained from a hospital waste incinerator in Klang, Malaysia. The produced ash was melted at 1200 °C and cooled at room temperature. The slag was crushed with a hammer and ground for analysis. X-ray diffraction (XRD) analysis was conducted by X-ray diffractometer (Siemens D-5000) using a dry sample powder (20–30 μm). The setting conditions for XRD were: Cu Kα radiation, 40 keV accelerating voltage, 30 mA current, 2–60° scanning range and 0.02° step scan speed. The X-ray fluorescence (XRF) was performed by automated Philips PW 1480 spectrometer. The specimen for XRF analysis was prepared by mixing 0.4 g of samples and 4 g of 100 Spectroflux, giving a dilution ratio of 1:10. The homogeneous mixtures, placed in Pt–Au crucibles, were treated for 1 h at 1000 °C in an electrical furnace. The homogeneous melted slag was recast into 2 mm thick, 32 mm diameter glass beads.

The total metal concentrations in the slag were analyzed according to a US EPA approved method [4]. The slag was digested in 10 ml of (1:4) hydrochloric acid (HCl) and 4 ml of (1:1) nitric acid (HNO₃) followed by heating at 85 °C for 30 min. Extractants were filtered by filter paper (S&S) and made up to 100 ml volume. The metal concentrations in the all extraction solutions were determined by inductively coupled plasma mass spectrometry (ICP–MS).

2.2. Leaching experiments

The leaching of metals in the ash and slag was conducted according to the EPA extraction procedure (EP) toxicity test [5] with some modification. The EPA method consists of extracting the triplicate product with distilled water at a ratio of 1:16 at different pH values during 24 h. Tests were carried out at pH 3 and 5. The different pH values were adjusted using 0.5N acetic acid (HOAc). The ratio of solid to liquid at the end was 1:20. The solutions were filtered with 0.45 μm membrane filter (Whatman) and were analysed with ICP–MS.

2.3. Fractionation of metals

The Tessier et al. [6] procedure of sequential chemical extraction was used to fractionate the metals in the ash and slag. Extraction was performed in a 250 ml flask. The metals were fractionated into five fractions:

(F_1) exchangeable; 5.0 g of slag was added with 100 ml 1 M sodium acetate (NaOAc) at pH 8.2 and shaken for 1 h;

(F_2) bound to carbonate; residue from exchangeable fraction (F_1) was shaken with 100 ml 1 M NaOAc at pH 5.0 (adjusted with HOAc) for 5 h;

(F_3) bound to Fe–Mn oxides; 100 ml 0.04 M hydroxylamine hydrochloride ($NH_2OH \cdot HCl$) in 25% HOAc was added to residue from carbonate fraction (F_2) and heated at $90 \pm 5\,°C$ for 5 h;

(F_4) bound to organic matters; 15 ml 0.02 M HNO_3 and 25 ml 30% hydrogen peroxide (H_2O_2) (pH 2 adjusted with HNO_3) were added to residue from Fe–Mn oxides fraction (F_3) and heated at $80 \pm 5\,°C$ for 2 h. Another aliquot of 15 ml 30% hydrogen peroxide (H_2O_2) (pH 2 adjusted with HNO_3) was added and heated again at $80 \pm 5\,°C$ for 3 h. After cooling to room temperature, 25 ml 3.2 M ammonium acetate (NH_4OAc) in 20% HNO_3 was added and agitated for 30 min;

(F_5) residual fraction determined by digestion of 0.5 g (dry weight) of residue from bound to organic matter fraction (F_4) with $HNO_3:H_2O_2:HF:HCl$ (1:1:3:3).

After each extraction, the separation was achieved by centrifuging and the supernatant was analysed by ICP–MS.

2.4. Quality control

All glassware was soaked in 50% HNO_3 for 1 day, rinsed with distilled water and sealed with aluminium foil prior to use. All chemicals used were analytical grade and obtained from Fisher, UK. Nano pure water (Barnstead, USA) was used for preparation of all solutions.

Throughout the entire analytical process, blank was included for each set of samples. Standard addition method was applied through digestion procedure outlined for samples prior to analysis by ICP–MS. Analytical precision and accuracy of the methods was assessed by analyzing standard reference material (SRM) with each analytical set. The SRM (S-5) was supplied from International Atomic Energy Agency (IAEA), Austria. The results were comparable with the published IAEA values.

3. Results and discussion

3.1. Characterization of the slag

Table 1 shows that produced slag contained large amounts of SiO_2 (58.28%), CaO (11.56%) and Al_2O_3 (10.32%), while the content of other metal oxides is less than 10%. The major metals identified in the produced slag were Sn, Ni, Cu, Ba and B. As shown in Fig. 1, XRD analysis revealed the crystal structure of the melted slag, which can be categorized as poor to moderate crystal formation. The main crystals of produced slag are quartz (SiO_2),

Table 1
Chemical composition of slag produced from incinerated hospital waste[a]

Components	Values (wt.%)	Components	Values (mg/kg)
SiO_2	58.28 ± 6.78	As	6.1 ± 0.3
CaO	11.56 ± 1.56	Ag	0.04 ± 0.01
Al_2O_3	10.32 ± 1.03	B	186.6 ± 15.58
Na_2O	8.80 ± 1.98	Ba	222.81 ± 29.36
Fe_2O_3	3.77 ± 0.23	Cd	0.17 ± 0.02
TiO_2	2.02 ± 0.45	Cr	94.6 ± 8.32
MgO	1.48 ± 0.15	Cu	697.9 ± 44.23
K_2O	0.87 ± 0.08	Co	4.6 ± 0.14
P_2O_5	0.84 ± 0.08	Ni	278.4 ± 23.35
MnO	0.07 ± 0.01	Pb	15.7 ± 2.58
L.O.I	0.00	Sn	1410.0 ± 241.02
Others	1.99 ± 0.09	Zn	72.0 ± 9.63
		Hg	0.05 ± 0.01

[a] All data are the means of six samples.

kaolinite ($Al_2Si_2O_5(OH)_4$), albite ($NaAlSi_3O_8$) and gibbsite ($Al (OH)_3$). Nishida et al. [7] stated that the presence of crystal structures in the slag is influential in preventing the heavy metals from leaching. This observation is further verified in our studies on leaching test presented in Section 3.2.

3.2. Leaching experiments

The results in Table 2 showed metal concentrations found in leachate from incinerated hospital waste ash and produced slag, tested according to the EPA EP toxicity test. Among
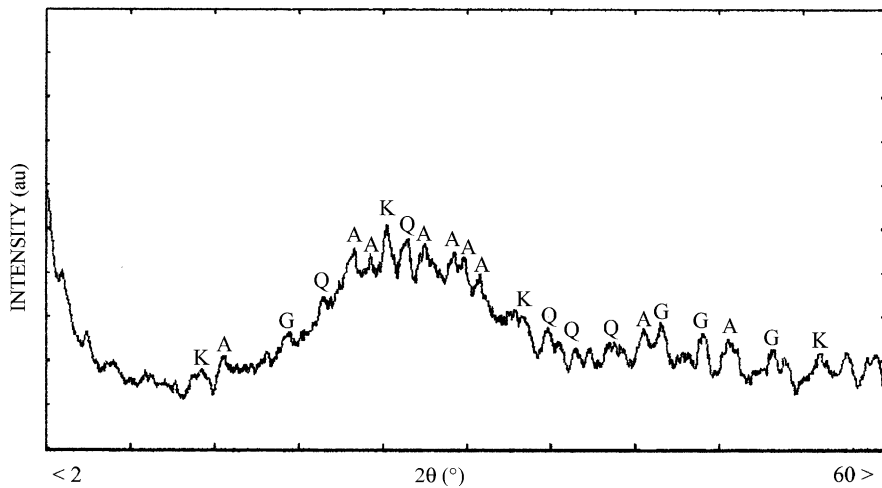

Fig. 1. XRD pattern of produced slag from incinerated hospital waste (Q: quatrz, K: kaolinite, A: albite, G: gibbsite).

Table 2
Leaching of metals from slag and incinerated hospital waste ash[a]

Metal (mg/l)	Slag		Ash		US EPA standard (mg/l)[b]
	pH 3	pH 5	pH 3	pH 5	
As	2.04 ± 0.25	0.004 ± 0.001	9.11 ± 1.54	5.11 ± 0.97	5
Ag	0.02 ± 0.01	0.01 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	5
Ba	26.1 ± 3.86	3.2 ± 0.28	48.19 ± 5.24	6.8 ± 1.87	100
Cd	ND[c]	ND	8.20 ± 2.53	4.17 ± 0.97	1
Cr	2.40 ± 0.18	0.04 ± 0.01	10.08 ± 1.69	0.11 ± 0.06	5
Cu	31.26 ± 5.98	25.44 ± 3.89	67.12 ± 12.36	49.14 ± 4.63	100
Hg	ND	ND	0.97 ± 0.04	0.97 ± 0.09	0.2
Ni	1.96 ± 0.14	0.89 ± 0.09	9.74 ± 2.28	6.73 ± 0.12	100
Pb	0.09 ± 0.01	0.08 ± 0.01	6.90 ± 1.75	1.40 ± 0.09	5
Se	0.06 ± 0.01	ND	2.83 ± 0.19	0.97 ± 0.05	1

[a] All data are the means of six samples.
[b] US EPA maximum limits for disposal of waste to landfill [8].
[c] ND: not detected.

metals, Cd and Hg were not detected in the leachate from the slag at both pH 3 and 5. In the leachate at pH 5, Se was not detected, while the release of other metals was found to be in order Cu > Ba > Ni > Pb > Cr > Ag > As. As the pH was decreased to 3, the concentration of metals in leachate increased. The results showed that pH 3 favored the mobilities of the studied metals in order Cu > Ba > Cr > Ni > As > Pb > Se > Ag. In general, metal concentration in leachate from the slag at both pH 3 and 5 were found to be less than maximum limits stated by US EPA [8]. Furthermore, results presented in Table 2, also showed that the concentration of the metals in the leachate from the slag were significantly lower (*t*-test, $P < 0.05$) than the metal concentrations in leachate from the ash. Therefore, it can be accepted that melting of ash had resulted in great reduction of metal leachability.

3.3. Fractionation of metals

The sequential chemical was used to categorize chemical form of metals in the slag and incinerated hospital waste ash and the results are presented in Figs. 2 and 3, respectively.

In the case of slag, the exchangeable fraction (F_1) accounted for 0.16–10.75% of the total extractable metal in the slag. Among the metals examined, Cu showed the highest exchangeable fraction (10.75%), while Ni presented only 0.16% bound to this fraction. The percentage of metals bound to the exchangeable fraction (F_1) were in order Cu > Ba > Cr > As > B > Pb > Zn > Cd > Sn > Co > Ni.

The percentage of metals partitioned towards the carbonate fraction (F_2) ranged from 2.2 to 14.6% of the total fractions. According to the results, the sequence of metal percentages bound to the carbonate fraction (F_2) were found to be Cu > Ba > Cr > As > Sn > Zn > Pb > B > Cd > Ni > Co.

On the basis of these results, Cu, Ba and Cr showed the highest preference to bind to carbonate (10.0–14.6%) and exchangeable (9.65–10.75%) fractions. This finding was
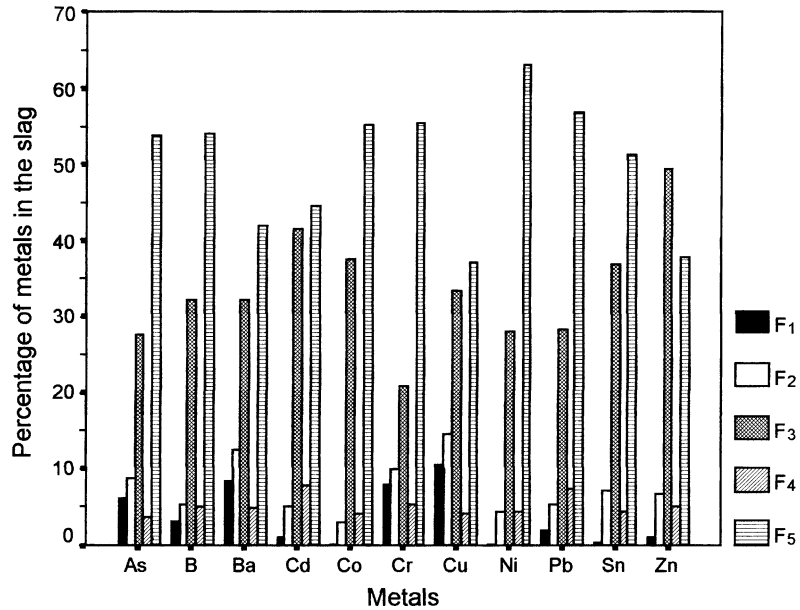
Fig. 2. Metal fractionations in the slag produced from incinerated hospital waste (bound to exchangeable (F_1) bound to carbonate (F_2) bound to Fe–Mn oxides (F_3) bound to organic matter (F_4) bound to residual (F_5)).

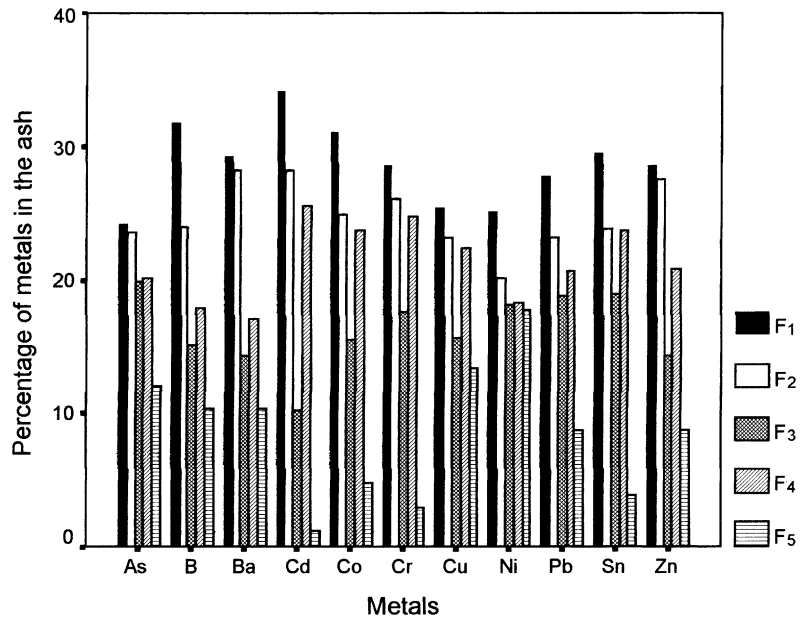

Fig. 3. Metal fractionations in the incinerated hospital waste ash; (bound to exchangeable (F_1) bound to carbonate (F_2) bound to Fe–Mn oxides (F_3) bound to organic matter (F_4) bound to residual (F_5)).

similar to results obtained in leaching experiments of slag, whereby the highest leachable metals observed were Cu, Ba and Cr.

The percentage of metals associated with the organic fraction (F_4) in the slag were in the range of 3.64–7.77%. Since most of the organic matter was oxidized during incineration and melting process, therefore the lower metal content bound to this fraction was expected. The increasing percentage of metal bound to the organic matter fraction (F_4) can be listed as Cd > Pb > Cr > B > Zn > Ba > Ni > Sn > Cu > Co > As.

As shown in Fig. 2, all metals studied exhibited the highest preference to be bound to Fe–Mn oxides (F_3) and residual fractions (F_5) compared to other fractions. Results showed that over 37–64 and 20–49% of metals were found to be associated to residual fraction (F_5) and Fe–Mn oxides fraction (F_3), respectively. The increasing order of metal contents bound to residual fraction (F_5) were Ni > Pb > Cr > Co > B > As > Sn > Cd > Ba > Zn > Cu, while for Fe–Mn oxides fraction (F_5) were in order of Zn > Cd > Co > Sn > Cu > B > Ba > Pb > Ni > As > Cr.

In general, the metal contents bounded to different fractions in the slag followed the order: residual (F_5) > Fe–Mn oxides (F_3) > carbonate (F_2) > organic matter (F_4) > exchangeable (F_1). In the case of ash as shown in Fig. 3, the percentage of metals bound to different fractions followed the order: exchangeable (F_1) > carbonate (F_2) > organic matter (F_4) > Fe–Mn oxides (F_3) > residual (F_5). Comparison between fractionation of metals in the ash and slag revealed that melting process had caused great increase of the metal bound to the residual fraction (F_5) and great reduction of metal bound to exchangeable (F_1) and carbonate fractions (F_2).

Elliot et al. [9] documented that metal contents in the exchangeable (F_1) and carbonate fractions (F_2) represent the potential availability and leaching of metals. In contrast, metals associated with the residual fraction (F_5) are considered stable [10]. Thus, the low extraction mobility of metals in the exchangeable and carbonate fractions (mobile fractions) and higher concentration of metals, to remain in residual fraction (stable fraction) in the slag will provide very low leaching risk to the environment.

4. Conclusion

High temperature melting treatment of incinerated hospital waste ash produced stabilized product, which is proven to be non-hazardous. This can be explained by the association of metals in more stable fraction, such as residual fraction. Results from US EPA leaching tests also verified that metals stabilized in slag were not leached beyond the standard, therefore concluding that the slag can be classified as non-hazardous product.

Acknowledgements

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