

Leaching characteristics of slag from the melting treatment of municipal solid waste incinerator ash

K.L. Lin*, C.T. Chang

Department of Environmental Engineering, National I-Lan University, I-Lan 260, Taiwan, ROC

Received 26 July 2005; received in revised form 18 November 2005; accepted 24 November 2005

Available online 6 January 2006

Abstract

This study investigated the composition and leaching characteristics of municipal solid waste incinerator (MSWI) ash and slag. The modified slags were characterized after the melting of MSWI ash mixtures at 1400 °C for 30 min. The ash mixtures were composed of different types of MSWI ash, including cyclone ash, scrubber ash and bottom ash, in various proportions. The results indicate that the Cd leaching concentration of the cyclone ash and the Pb leaching concentration of the scrubber ash reached 1.82 and 8.7 mg/L, respectively, which exceeds the ROC EPA's current regulatory thresholds, and can thus be classified as hazardous. The results of the analysis of the metal content and the leaching behavior of heavy metals, showed high concentrations of Cu and Zn, but a low leaching ratio of these metals. Concerning the characteristics of the modified slags, the X-ray diffraction patterns of the MSWI fly ash slag showed that it contained large amounts of glass. The toxicity characteristic leaching procedure (TCLP) leaching concentrations of the target metals of all the slags, met the ROC EPA's regulatory thresholds. The leaching concentrations of heavy metals in the F- and B1-slag were lower than those in the cyclone and the bottom ash, because there was a high amount of SiO₂, which formed a net-like structure in the bottom ash.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Municipal solid waste incinerator; Fly ash; Melting treatment; Leachability

1. Introduction

Landfill site limitations and increasing disposal costs have hastened efforts to adopt incineration technologies and energy recovery strategies for managing municipal solid waste in Taiwan. These incinerators will eventually be capable of processing 90% of the island's municipal solid waste, but will produce more than 2000 t of incinerator residues each day, including 400 t of hazardous fly ash, which needs to be managed appropriately 90% of the total municipal solid waste incinerator (MSWI) residues is bottom ash and 10% is fly ash. Municipal solid waste incinerator fly ash contains high levels of leachable heavy metals, polychlorinated dibenzodioxins dibenzofurans [1] and salts, and is thus usually classified as hazardous waste [2,3].

Mineralogical studies have found that municipal solid waste incinerator bottom ash is composed of equal amounts of fine ash material and melted components, of which half have crystallized,

small quantities of metallic components, ceramics and stones. Minerals such as calcite, ettringite, hematite, quartz, gypsum and silicate have also been identified [4]. However, the bottom ash contains potentially toxic elements, which can leach into soils and sediments, which is a concern. For example, laboratory and field studies have indicated that these leachates contain high soluble salt concentrations [5,6] and the fine fraction often contains heavy metals [7].

Due to grow urbanization and industrialization, the amount of MSWI residues has increased very rapidly. In addition, their composition is very complex. Various treatment methods for MSWI residues have been investigated and utilized. Several approaches have been used to solidify/stabilize the more hazardous fly ash. These include acid extraction, neutralization with exhaust gases, chemical fixation, sintering and melting. Heat treatment can be used to reduce the heavy metal content in the fly ash by evaporating the volatile heavy metal compounds from the ash, which immobilizes the non-volatile heavy metals into a primary matrix material consisting of inert silicates. Melting treatment is another vitrification technology that has been identified as a potentially effective tool that can immobilize heavy

* Corresponding author. Tel.: +886 3 9357400x749; fax: +886 3 9367642.
E-mail address: kllin@niu.edu.tw (K.L. Lin).

- Heavy metal leachability (TCLP): SW846-1311. The extraction procedure requires the preliminary evaluation of the pH characteristic of the sample to determine the proper extraction fluid necessary for the experiment. After testing, extraction fluid #B (pH 2.88 ± 0.05) was selected for the TCLP analysis. This fluid was prepared by adding 5.7 mL of acid to 500 mL of double-distilled water, diluted to a volume of 1 L. A 25 g sample was placed in a 1 L Erlenmeyer flask, and a 500 mL of extraction fluid was added to each Erlenmeyer flask. The samples were then agitated for 18 h with an electric vibrator. The slurry was filtered using 6–8 μm pore size Millipore filter paper. The leachates were preserved in 2% HNO_3 .
- Heavy metal concentration: The heavy metal concentrations in the MSWI ash and slag samples were confirmed by ICP-AES. The samples were crushed, and the heavy metals were extracted by acid ($\text{HF}:\text{HClO}_4:\text{HNO}_3 = 2:1:1$).
- Pouring point: The pouring point of the ash was determined by ASTM D1857 method.
- Chemical composition: X-ray fluorescence (XRF) was performed with an automated RIX 2000 spectrometer. The specimens were prepared for XRF analysis by mixing 0.4 g of the sample and 4 g of 100 Spectroflux, at a dilution ratio of 1:10. Homogenized mixtures were placed in Pt–Au crucibles then treated for 1 h at 1000°C in an electrical furnace. The homogeneous melted sample was recast into glass beads 2 mm thick and 32 mm in diameter.
- Mineralogy: The XRD analysis was carried out using a Siemens D-5000 X-ray diffractometer with Cu $\text{K}\alpha$ radiation and 2θ scanning, ranging between 5 and 70° (2θ). The XRD scans were run in 0.05° steps, with a 1 s counting time.

3. Results and discussion

3.1. Characterization of MSWI residues

Fig. 2 shows the speciation of the cyclone ash, as identified by the XRD techniques. The results indicate that the major components were quartz (SiO_2), anhydrite (CaSO_4), microcline (KAlSi_3O_8), calcium chloride (CaCl_2), sylvite (KCl) and halite (NaCl). Fig. 3 shows the speciation of the scrubber ash.

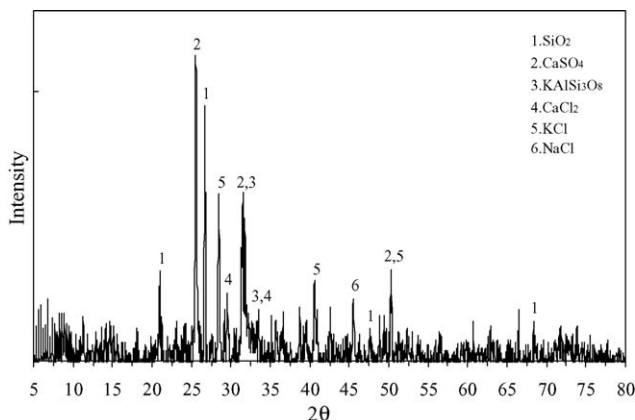


Fig. 2. XRD patterns of cyclone ash.

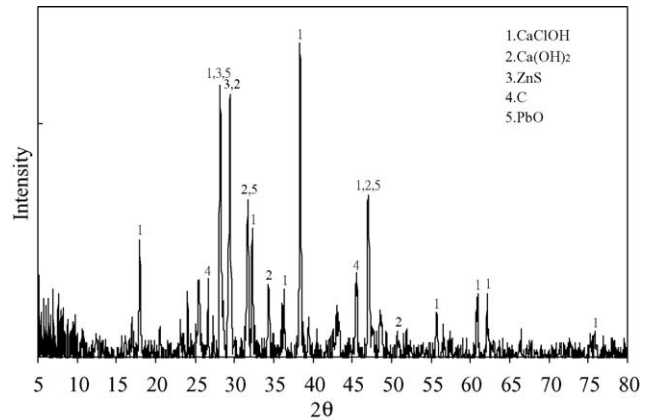


Fig. 3. XRD patterns of scrubber ash.

The results indicate that the major components were CaClOH , Ca(OH)_2 , ZnS , C and PbO . Fig. 4 shows the speciation of the bottom ash. The results indicate that the major components were SiO_2 , CaCO_3 , $\text{Ca}_2\text{SiO}_3\text{Cl}_2$, PbO and $\text{Al}_6\text{Ca}_2\text{O}_{13} \cdot 3\text{H}_2\text{O}$.

The major components in the cyclone ash are shown in Table 2, with SiO_2 , CaO and Al_2O_3 , the most abundant, comprising 28.3, 22.7, and 12.6% (by wt.), respectively. The next most abundant components are K_2O , Fe_2O_3 and SO_3 , contributing about 6.1, 3.4 and 3.2%, respectively. The ash had a basicity (defined as CaO/SiO_2) of 0.8, and a pouring point of approximately 1200°C . The major components in the scrubber ash are shown in Table 2, with CaO and SO_3 comprising 42.3 and 7.3%, respectively. The next most abundant components are Na_2O , K_2O and Fe_2O_3 , contributing about 3.5, 3.0 and 0.73%, respectively. CaO was found in larger amounts in the scrubber ash, due to the injection of a lime solution to remove acid gas. The major components in the bottom ash are shown in Table 2, with CaO and SiO_2 comprising 26.1 and 25.8%, respectively. The next most abundant components are Fe_2O_3 , Al_2O_3 and Na_2O , contributing about 10.3, 6.3, and 3.9%, respectively. Most of the metal oxides having a low volatility, such as Fe_2O_3 , were found to have large amounts in the bottom ash. A large amount was found in the cyclone ash and scrubber ash, but only a small amount of Cl was present in the bottom ash. From these results one can infer that the air pollution control devices removed a sig-

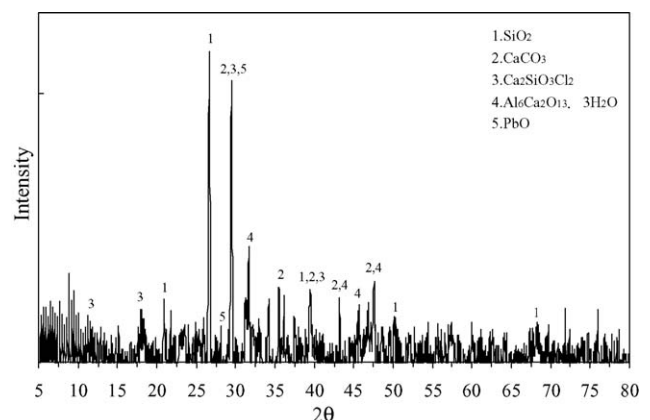


Fig. 4. XRD patterns of bottom ash.

Table 2
Composition of the MSW cyclone ash, scrubber ash, bottom ash and the modified slags

Composition (%)	Cyclone ash	Scrubber ash	Bottom ash	F	S1	S2	S3	B1	B2	B3	M1	M2	M3
SiO ₂	28.33	0.63	25.79	38.87	32.41	33.62	34.13	31.07	33.56	33.97	29.26	34.69	29.83
CaO	22.77	42.25	26.14	27.22	33.56	30.94	31.06	26.44	25.59	25.08	36.22	35.4	33.92
Al ₂ O ₃	12.57	<0.01	6.33	23.26	14.87	16.00	15.77	8.87	12.35	13.09	9.86	12.06	8.38
Fe ₂ O ₃	3.43	0.73	10.33	5.33	3.51	2.50	3.56	11.21	7.82	7.12	7.54	5.45	10.39
MgO	2.01	0.35	0.82	3.60	2.43	2.40	2.56	1.40	1.86	1.95	1.78	2.11	1.49
Na ₂ O	<0.01	3.51	3.92	1.23	0.81	1.12	1.33	2.39	2.27	2.32	0.94	0.94	1.33
Cl ⁻	8.82	35.62	1.16	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.04	0.03	0.02
K ₂ O	6.05	3.02	1.13	–	0.39	0.55	0.66	0.92	1.15	1.21	0.33	0.37	0.43
SO ₃	3.2	7.25	0.47	0.20	0.06	0.10	0.12	0.09	0.14	0.16	0.43	0.32	0.33
Ca/SiO ₂	0.80	67.06	1.01	0.70	1.04	0.92	0.91	0.85	0.76	0.74	1.24	1.02	1.14

nificant portion of the metal and organic chlorides via deposition into solid particles.

The basicity of the ash is shown in Table 2. The quantity of oxide material can be estimated from the total amount of the analyzed element, and the basicity of the ash can be calculated from the CaO and SiO₂ ratio. SiO₂ was a major compound in the bottom ash, but was least in the scrubber ash. The basicities of the cyclone, scrubber and bottom ashes were 0.8, 67.06 and 1.01, respectively. The scrubber ash indicated higher basicity than the bottom ash. The scrubber ash showed the highest basicity, due to the injection of the lime solution. The basicity of the ash from bottom ash was also high.

3.2. Total heavy metals and leaching concentration of MSWI ashes

The heavy metal content and concentrations in the TCLP leachates for the targeted heavy metals were examined, and are listed in Table 3. The leaching concentrations, obtained by toxicity characteristic leaching procedure test, are presented in Table 3.

In the case of cyclone ash and scrubber ash, most of the heavy metal concentrations were higher than those in the bottom ash, as shown in Table 3. This could be explained as due to the fact that the vaporized metals had condensed and aggregated on the surface of the cyclone and scrubber ash, due to the temperature in the flue gas cooling system. The highest metal concentration was observed in the bag filter, which collected particles having a larger specific surface area. The cyclone ash had higher Pb, Cr and Zn leaching ratios than did the bottom ash. This means that bottom ash might consist of more complicated compounds, such as highly polymerized silicates and aluminosilicates, for example rock minerals that are not easily leached out [11]. The results of the metal content analysis, as well as the leaching behavior of heavy metals, the cyclone ash, scrubber ash and bottom ash all showed high concentrations of Zn and Pb, but low leaching ratios of these metals. The results for the analysis of the metal content and the leaching behavior of heavy metals, showed high concentrations of Cu and Zn, but low leaching ratios of these metals. In particular, the cyclone ash Cd leaching concentration and the scrubber ash Pb leaching concentration reached 1.8 and 8.7 mg/L, respectively, exceeding current the ROC EPA regulatory thresholds, thus being

classified as hazardous. It could be difficult to explain all the leaching characteristics of heterogeneous MSWI ash, because leaching is dependent on many physicochemical influences [12]. However, these results are still worthwhile, as they show the irregularity of the heavy metal leaching characteristics of the ash collected from different locations in the municipal solid waste incinerator.

3.3. Composition characterization of MSWI fly ash slag

Table 4 shows the XRF analysis results of the different slags. Table 2 lists the major components of the MSWI-modified slag used in this study. The slag was composed of SiO₂ (29–39%), CaO (25–36%), and Al₂O₃ (9–23%). The basicity of the slags ranged from 0.7 to 1.24. The X-ray diffraction patterns of the MSWI fly ash slag are shown in Fig. 5. They show that the slag contained large amounts of glass. The XRD patterns results

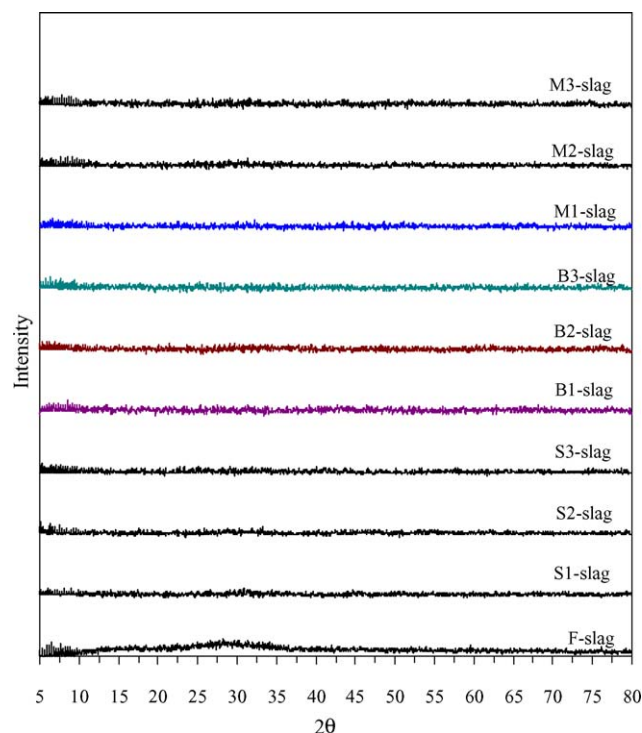


Fig. 5. XRD patterns of slags produced from MSWI ash.

Table 3
Total heavy metals and TCLP leaching concentrations of municipal solid waste incinerator residues

Sample	Pb	Cd	Cr	Cu	Zn
Cyclone ash					
Total concentration (mg/kg) ^b	1284 ± 14.8 ^a	80 ± 1.7	811 ± 24.6	1409 ± 89.1	7115 ± 163.0
TCLP concentration (mg/L)	0.72 ± 0.01	1.82 ± 0.02	4.30 ± 0.05	0.61 ± 0.01	16.20 ± 0.30
Leachate rate (%)	0.05	2.2	0.5	0.04	0.23
Scrubber ash					
Total concentration (mg/kg)	4453 ± 84.1	333 ± 5.9	195 ± 10.7	90 ± 13.8	12374 ± 256.0
TCLP concentration (mg/L)	8.70 ± 0.14	0.62 ± 0.02	0.22 ± 0.01	0.49 ± 0.01	4.63 ± 0.10
Leachate rate (%)	0.20	0.19	0.01	0.54	0.04
Bottom ash					
Total concentration (mg/kg)	5195 ± 33.2	27 ± 0.6	276 ± 12.4	432 ± 47.9	8352 ± 184.0
TCLP concentration (mg/L)	0.59 ± 0.05	0.24 ± 0.01	0.26 ± 0.01	5.49 ± 0.03	18.01 ± 0.08
Leachate rate (%)	0.01	0.89	0.09	1.27	0.22
Regulatory limits	5	1	5	15	–

^a Mean ± S.D. (*n* = 8).

^b Analyzed by ICP-AES after HF/HClO₄/HNO₃ digestion.

Table 4
Total heavy metal and TCLP leaching concentrations of MSWI slags

Sample	Pb ^a	Cd ^b	Cr ^c	Cu	Zn
F-slag					
Total conc. (mg/kg)	295.1 ± 5.71	5.8 ± 0.02	695.3 ± 6.19	604.4 ± 10.54	6480 ± 15.26
TCLP conc. (mg/L)	ND	ND	0.27 ± 0.03	0.25 ± 0.09	14.20 ± 0.25
S1-slag					
Total conc. (mg/kg)	178.1 ± 3.47	9.3 ± 0.02	2838.5 ± 14.34	20.0 ± 0.33	8971.1 ± 33.94
TCLP conc. (mg/L)	0.27 ± 0.02	0.14 ± 0.01	0.65 ± 0.01	0.91 ± 0.02	11.57 ± 1.43
S2-slag					
Total conc. (mg/kg)	184.1 ± 3.85	8.0 ± 0.04	2708.7 ± 11.62	33.6 ± 0.66	7733.7 ± 24.52
TCLP conc. (mg/L)	0.27 ± 0.01	0.12 ± 0.02	0.89 ± 0.02	5.46 ± 0.14	7.64 ± 1.10
S3-slag					
Total conc. (mg/kg)	193.0 ± 2.69	10.7 ± 0.12	2822.3 ± 13.22	37.2 ± 0.68	7424.3 ± 16.75
TCLP conc. (mg/L)	0.09 ± 0.01	0.11 ± 0.01	0.85 ± 0.03	5.14 ± 0.11	7.87 ± 1.06
B1-slag					
Total conc. (mg/kg)	609.4 ± 7.24	5.3 ± 0.03	1719.3 ± 9.77	136.3 ± 4.84	4949.6 ± 17.79
TCLP conc. (mg/L)	0.35 ± 0.03	0.17 ± 0.01	ND	0.19 ± 0.01	12.03 ± 1.41
B2-slag					
Total conc. (mg/kg)	571.5 ± 7.02	9.3 ± 0.11	2433.0 ± 10.16	80.4 ± 1.74	6187.0 ± 11.64
TCLP conc. (mg/L)	0.78 ± 0.05	0.08 ± 0.01	0.26 ± 0.01	1.69 ± 0.11	4.86 ± 0.89
B3-slag					
Total conc. (mg/kg)	534.4 ± 5.83	12.0 ± 0.05	2384.3 ± 13.68	73.6 ± 1.25	7115.0 ± 24.33
TCLP conc. (mg/L)	1.04 ± 0.08	0.10 ± 0.03	0.36 ± 0.02	1.42 ± 0.20	6.02 ± 0.77
M1-slag					
Total conc. (mg/kg)	311.7 ± 2.38	10.7 ± 0.04	2368.1 ± 11.19	65.9 ± 1.59	8661.7 ± 30.49
TCLP conc. (mg/L)	0.44 ± 0.01	0.19 ± 0.04	ND	0.10 ± 0.01	10.18 ± 1.36
M2-slag					
Total conc. (mg/kg)	497.3 ± 4.65	2.7 ± 0.01	1881.5 ± 6.22	104.5 ± 2.93	8043.0 ± 36.95
TCLP conc. (mg/L)	0.44 ± 0.02	0.19 ± 0.03	ND	0.07 ± 0.01	14.34 ± 2.10
M3-slag					
Total conc. (mg/kg)	682.8 ± 8.99	4.0 ± 0.03	1540.9 ± 8.67	136.3 ± 4.48	6805.7 ± 22.87
TCLP conc. (mg/L)	0.41 ± 0.02	0.19 ± 0.04	NDs	0.10 ± 0.02	11.57 ± 1.58
Regulatory limits	5	1	5	15	–

Mean ± S.D. (*n* = 8).

^a Pb detection limits <0.016 mg/L.

^b Cd detection limits <0.014 mg/L.

^c Cr detection limits <0.016 mg/L.

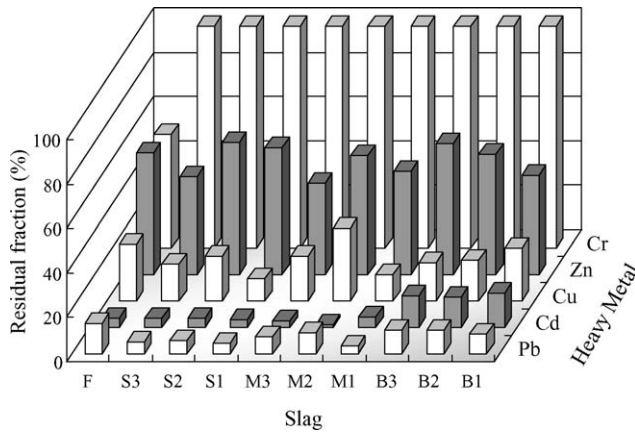


Fig. 6. Residual fraction of heavy metals under melting treatment.

indicate a significant difference in the MSWI ash samples and the slag structures (Fig. 2 through Figs. 4 and 5); the former has a much more crystalline structure while the latter shows an amorphous glassy matrix.

3.4. Residual fraction of heavy metals after melting treatment

The residual fraction of each of the heavy metals in slag is defined by:

$$\text{residual fractions of heavy metals} = \frac{\text{mass of heavy metal in slag sample}}{\text{mass of heavy metal in original ash}}$$

The residual fractions of heavy metals in MSWI slag are shown in Fig. 6. Several heavy metals, known to be volatile, immediately vaporized during the melting process. This kind of element easily became volatile during the ash melting process. Above 1400 °C, heavy metals, such as lead and cadmium were almost completely volatilized, as shown in Fig. 6. A another group, classified as semi-volatile or volatile metals for example Zn, remained at values of about 44–60% in slag, while the rate of vaporization/dispersion from the furnace was in the range of 40–56%. However, the collection rate of Cu showed that about 10–33% remained in the slag. It is thought that the Cu had been converted to Cu₂O, which has a relatively high boiling point, so that this volatile compound was relatively less [13]. Of the non-volatile metal group, about 96–97% of the Cr was retained in the slag due to the low volatility. The rate of vaporization/dispersion was only 3–4%, because Cr is known to be converted into CrO₃, in high temperature oxidation conditions, which is a relatively more stable compound [14]. The major chromium species found in the fly ash were chromium chloride (b.p. 1200–1500 °C) and chromium oxide (b.p. 1900 °C), which both have high boiling and melting points. It was confirmed that the emission behavior of the volatile metals in the melting process varied with the ash composition.

3.5. Leaching of slags on volatile metal emission

The resultant slags were analyzed for their leachability characteristics using the toxicity characteristic leaching procedure. The results are shown in Table 4.

High vapor pressure metals, such as Cd, Pb, and Zn, are difficult to retain in the melt and the slag because they are emitted during melting treatment.

Melting treatment was found to decrease the leaching concentrations of the slag samples, as shown in Table 4. This indicated that the melting process decreased the TCLP leachability of the heavy metals in comparison with the original ash. The leaching concentrations of heavy metals in the F- and B1-slag were lower than those in the cyclone ash and the bottom ash, because of the large amount of SiO₂ with a net-like structure in bottom ash. Usually, most of the heavy metals could be fixed in this net-like structure, so were not easily extracted. The maximum allowable leachable leachate concentrations were 5, 1 and 5 mg/L for Pb, Cd and Cr, respectively. The leaching concentrations of the vitrified products and of the five heavy metals all met the EPA limit. Based on these results, the TCLP leaching concentrations for the target metals of all slags were all met the ROC EPA's regulatory thresholds. Cheng et al. confirmed that the fundamental structure of silicates basically consists of four O²⁻ at the apices of a regular tetrahedron surrounding and coordinated by one Si⁴⁺ at the center. The strength of any single Si–O bond is just equal to one-half of the total bonding energy available in the oxygen ion. Every O²⁻ has the potentiality of bonding to another silicon ion and entering into another tetrahedral grouping, thus uniting the tetrahedral groups through the shared oxygen, forming the great variety of silicate structures. The low leachability characteristics of metals were thus presumably because the heavy metal ions replaced the parent ions (Al³⁺ and Ca²⁺) and were enclosed in the silicate framework [15].

4. Conclusions

From the obtained results, the following conclusions and some suggestions for subsequent treatment can be made:

1. The cyclone ash Cd leaching concentration and the scrubber ash Pb leaching concentration reached 1.8 and 8.7 mg/L, respectively, which exceeds the ROC EPA's current regulatory thresholds, and can thus be classified as hazardous.
2. The results of the metal content analysis, and the leaching behavior of heavy metals, showed high concentrations but low leaching ratios of Cu and Zn.
3. The X-ray diffraction patterns of the MSWI fly ash slag show that the slag contained large amounts of glass.
4. Above 1400 °C, heavy metals, such as Cr are non-volatile, whereas Pb and Cd are volatile.
5. The leaching concentrations of heavy metals in F- and B1-slag were lower than those in the cyclone ash and the bottom ash, because of the large amount of SiO₂ having a net-like structure that existed in bottom ash.

6. The TCLP leaching concentrations of the target metals in all the slags met the ROC EPA's regulatory thresholds.

References

- [1] B. Van der Bruggen, G. Vogels, P. Van Herck, C. Vandecasteele, Simulation of acid washing of municipal solid waste incineration fly ashes in order to remove heavy metals, *J. Hazard. Mater.* 57 (1998) 127–144.
- [2] J. Iori, J. Balg, Detoxification of municipal waste incineration residues by vitrification, *Residue Treat.* 6 (1995) 9–16.
- [3] K.S. Wang, K.L. Lin, Z.Q. Huang, Hydraulic activity of municipal solid waste incinerator fly ash slag blended eco-cement, *Cement Concrete Res.* 31 (2001) 97–103.
- [4] C.A. Johnson, S. Brandenberger, P. Baccin, Acid neutralizing capacity of municipal waste incinerator bottom ash, *Environ. Sci. Technol.* 29 (1995) 142–147.
- [5] C.S. Kirby, J.D. Rimstidt, Mineralogy and surface properties of municipal solid waste ash, *Environ. Sci. Technol.* 27 (1993) 652–660.
- [6] J.A. Meima, R.N.J. Comans, Geochemical modeling of weathering reactions in municipal solid waste incinerator bottom ash, *Environ. Sci. Technol.* 31 (1997) 1269–1276.
- [7] J.M. Chimenos, M.A. Fernandez, F. Espiell, Characterization of the bottom ash in municipal solid waste incineration, *J. Hazard. Mater.* A64 (1999) 211–222.
- [8] R. Cortez, H.H. Zaghoul, L.D. Stephenson, E.D. Smith, Laboratory scale thermal plasma arc vitrification studies of heavy metal-laden waste, *J. Air Waste Manage. Assoc.* 46 (1996) 1075–1080.
- [9] A. Jakob, S. Stucki, P. Kuhn, Evaporation of heavy metals during the heat treatment of municipal solid waste incinerator bottom ash, *Environ. Sci. Technol.* 29 (1995) 2429–2436.
- [10] C. Izumikawa, Metal recovery from bottom ash generated from vitrification process for MSW ash, *Waste Manage.* 16 (1996) 501–507.
- [11] C.A. Johnson, M. Kersten, F. Ziegler, H.C. Moor, Leaching behaviour and solubility controlling solid phases of heavy metals in MSWI ash, *Waste Manage.* 16 (1996) 129–134.
- [12] A. Kida, Y. Noma, T. Imada, Chemical speciation and leaching properties of elements in municipal incinerator ashes, *Waste Manage.* 16 (1996) 527–536.
- [13] G.J. Songa, K.H. Kima, Y.C. Seo, S.C. Kimb, Characteristics of ashes from different locations at the MSW incinerator equipped with various air pollution control devices, *Waste Manage.* 24 (2004) 99–106.
- [14] Y.W. Chang, P. Biswas, An Equilibrium analysis to determine the speciation of metals in an incinerator, *Combust. Flame* 93 (1993) 31–40.
- [15] T.W. Cheng, J.P. Chu, C.C. Tzeng, Y.S. Chen, Treatment and recycling of incinerated ash using thermal plasma technology, *Waste Manage.* 22 (2002) 485–490.