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Journal of Hazardous Materials B138 (2006) 594–603

Journal of Hazardous Materials

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Comparison of the characteristics of bottom and fly ashes generated from various incineration processes

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Received 17 March 2006; received in revised form 30 May 2006; accepted 30 May 2006
Available online 6 June 2006

Abstract

This study analyzed and compared the characteristics of bottom and fly ashes from three municipal solid waste incinerators (MSWIs) in Taiwan. Different incineration furnaces were investigated, including: (1) fluidized bed, (2) mass-burning, and (3) mass-burning linked rotary kiln. The particle size distribution, morphology, mineralogical and chemical composition, and leaching behavior of heavy metals of ash samples were evaluated. The results revealed that three types of incineration processes have different characteristic for ashes due to transportation and mixing system inside furnace. Particle size distribution indicated that 28.5% of MSWI-B bottom ash has lower than 180 μm and 61.2% of MSWI-A fly ash has larger than the 250 μm. The leaching concentration of Pb exceeded the regulatory level set by the Taiwan EPA in fly ashes from MSWI-B and MSWI-C, and thus must be considered hazardous wastes. Specifically, the leaching concentration of heavy metals of fly ashes from MSWI-A (fluidized bed incinerator) was lower than that of the others, and was corresponded to the regulatory levels. Therefore, a fluidized bed incineration process appears a potential of handling heavy metals for ashes. The result was also provided the valuable information for incinerator design and operation.

Keywords: Municipal solid waste incinerator; Bottom ash; Fly ash; Fluidized bed; Mass-burning; Rotary kiln

1. Introduction

Taiwan is a small island with a high population density. Because of rising levels of waste production and limited land space, incineration has become the primary technology for waste disposal. From 1990 to 2005, 20 incinerators were rapidly planned and built on Taiwan. These incinerators are expected to treat over 15,000 tonnes of solid wastes daily. As a byproduct of waste treatment, these incinerators produce residues containing bottom ashes and fly ashes. The amount of the bottom ash generated from the incinerator was approximately 10–15% of solid wastes and that of the fly ash obtained from different air pollution control devices (APCDs) was approximately 2–3% of solid wastes. Therefore, about 2250 tonnes of bottom ashes and 400 tonnes of fly ashes are generated daily in Taiwan. Table 1 lists the total waste incinerated, ash generated, and electric generation.

Previous studies on the characteristics of bottom and fly ashes concentrated on the heavy metal content and leaching behavior from a single MSWI [1,2]. Concerns have arisen in recent years regarding the comparative properties of different MSWIs residues. Abbas et al. [3] investigated the ash from two type fluidized bed combustion of MSW may have similar total contents of an element but still the water extractable contents can be very different. Jung et al. [4] identified distribution of metals and the influential factors (furnace capacity, furnace temperature and input waste) on metal concentrations from 19 mass-burning and seven fluidized bed incinerators residues. The results indicated metals (Sn, Cu, Cd, Sb and Se) have a high correlation with input waste. Li et al. [5] analyzed the characteristics of the solid residues from two types of MSWIs facilities (mass-burning and pyrolytic incinerators) in China indicated that fly ashes should be meet the definition of hazardous waste. Shim et al. [6] compared the leaching characteristics of heavy metals in Korean and Japanese MSWI ash. The leaching concentration of Pb exceeded the regulatory level in bottom and fly ash of both countries. Numerous previous works have studied the characteristics of bottom and fly ashes generated from different MSWIs,

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doi:10.1016/j.jhazmat.2006.05.099

Table 1
Information of incinerators of Taiwan (2004)

Incineration plant	Refuse incinerated (tonnes/year)	Total ashes (tonnes/year)	Bottom ash (tonnes/year)	(Bottom ash/refuse incinerated) × 100%	Fly ash (tonnes/year)	(Fly ash/refuse incinerated) × 100%	Electric power generation (1000 kW)
Neihu Refuse Incineration Plant	95479.95	16144.00	13250.37	13.88	2893.63	3.03	21062.09
Mucha Refuse Incineration Plant	230926.67	31447.81	27762.59	12.02	3685.22	1.60	71021.80
Peitou Refuse Incineration Plant	345223.28	54280.81	45344.42	13.13	8936.39	2.59	146929.96
Shulin Refuse Incineration Plant	355069.93	59289.57	51887.99	14.61	7401.58	2.08	166862.40
Hsintien Refuse Incineration Plant	254172.10	40864.33	36170.38	14.23	4693.95	1.85	115968.80
Bali Refuse Incineration Plant	468562.91	82861.17	69662.70	14.87	13198.47	2.82	221382.12
Taoyuan Refuse Incineration Plant	438347.84	85397.21	70988.61	16.19	14408.60	3.29	262506.60
Hsinchu City Refuse Incineration Plant	261190.70	47979.56	39741.14	15.22	8238.42	3.15	158475.43
Taichung City Refuse Incineration Plant	219882.17	34918.81	27699.34	12.60	7219.47	3.28	94291.21
Houli Refuse Incineration Plant	272847.09	53506.92	44958.44	16.48	8548.48	3.13	165717.68
Wujih Refuse Incineration Plant[a]	89458.73	17983.42	15089.31	16.87	2894.11	3.24	59329.45
Hsichou Refuse Incineration Plant	274840.73	47043.99	39530.80	14.38	7513.19	2.73	143083.40
Lutsao Refuse Incineration Plant	283725.16	55020.03	46268.62	16.31	8751.41	3.08	164997.50
Chiayi City Refuse Incineration Plant	85013.15	11817.45	9684.59	11.39	2132.857	2.51	20241.90
Tainan City Refuse Incineration Plant	239360.89	40489.37	33549.74	14.02	6939.63	2.90	108951.84
Renwu Refuse Incineration Plant	388598.74	81068.02	68457.82	17.62	12610.20	3.25	230417.30
Kangshan Refuse Incineration Plant	330880.64	60714.18	52264.41	15.80	8449.77	2.55	184211.90
Kaohsiung Refuse Incineration Plat	242063.00	36934.98	29938.01	12.37	6996.97	2.89	57104.33
Kaohsiung South Refuse Incineration Plant	453592.67	108387.28	88024.83	19.41	20362.45	4.49	237042.66
Kandin Refuse Incineration Plant	282268.46	58059.00	45649.04	16.17	12409.96	4.40	140322.40
Total	5611504.81	1024208	855923.2		168284.8		2769920.77

Source: collected from Taiwan EPA.
[a] Statistics levels of Wujih Refuse Incineration Plant have been beginning from September 2004.

with a particular focus on metal distribution. However, particle size distributions, morphology, mineralogical and chemical composition of bottom ash and fly ash from different incineration processes have rarely been investigated. Different incineration processes contained different types of incineration reactor and APCDs.

The characteristics of ashes were influenced by the incineration parameters, including furnace type, capacity, furnace temperature and waste input, and so on. Understanding incineration behavior is problematic owing to the complex combustion process involving various reactions. Therefore, many studies have performed to investigate single or multiple parameters of incineration behavior, including the effect of input waste composition, operating temperature on the distributions of heavy metals [7–11]. However, such laboratory studies, while useful, cannot accurately represent real incineration conditions. Therefore, the characteristics of incinerator ashes should be further studied. However, the characteristics of ashes from fluidized bed, mass-burning and rotary kiln have rarely been investigated. For the transportation and mixing system of three incineration processes, a fluidized bed is a uniform gas–solid system. The gas distribution inside the bed has provided a good solid mixing between wastes and bed materials. The addition of bed materials inside a fluidized bed provides better heat transfer efficiency and contact probability for wastes treatment. A mass-burning is a movable grate system by mechanical mixture to treat wastes. A rotary kiln is a rotating combustion system that keeps waste moving by a long retention time to achieve better contact

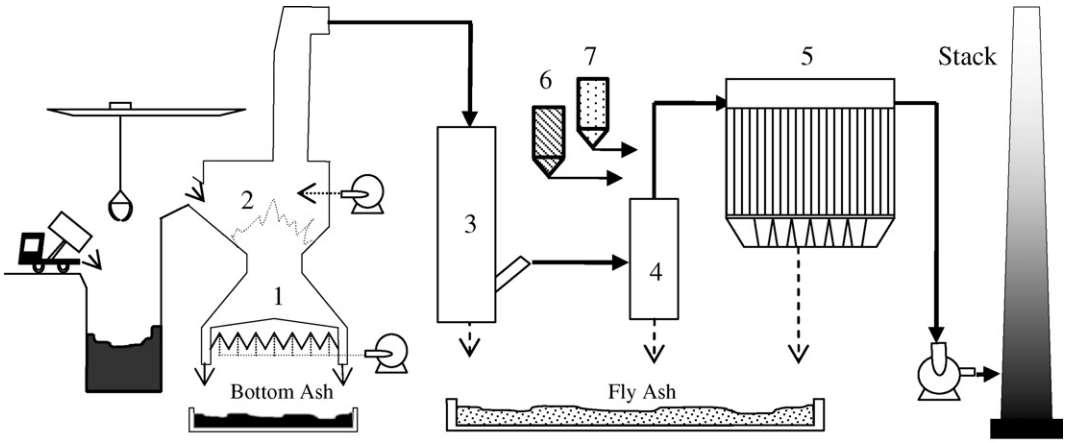

Fig. 1. Schematic diagram of the MSWI-A (fluidized bed): (1) primary combustion chamber, (2) secondary combustion chamber, (3) exhaust cooler, (4) heat exchanger, (5) bag filter, (6) activated carbon, and (7) lime.

between the kiln and the waste. Therefore, the characteristic of ashes from three incineration processes probably have different result due to the transportation system inside the incineration furnace.

Taiwan has installed a high density of incinerators within a short period. Most of incinerators are mass-burning type incinerators, and with relatively few being fluidized beds or rotary kiln incineration furnace. Although the characteristics of ashes have been widely analyzed, the effect of ashes from the various incineration processes has received little attention. Therefore, this study analyzed and compared the characteristics of bottom and fly ashes from three MSWIs. Mainly differences for three MSWIs are incineration furnaces and APCDs. Three types of incineration furnaces were studied, including fluidized bed, mass-burning and mass-burning links rotary kiln. Ashes are collected and analyzed, including particle size distribution, morphology, mineralogical, chemical composition and heavy metal leaching behavior. The results are helpful for understanding the characteristic of ashes from three incineration processes. The relative data of ashes from three incineration processes provide for modification if the existent furnace or APCDs may be change. Additionally, the information also provides a reference for designing of incineration process.

2. Materials and methods

2.1. Sample acquisition

Bottom and fly ashes were sampled from three types of MSW incinerators in Taiwan, designated A, B and C, respectively. Fig. 1 shows incineration system A. The reactor was a fluidized bed incinerator and handled 95 tonnes/day of MSW. The feed MSW was combusted in the sand bed, after which the flue gases produced were re-combusted in the freeboard at 800–950 °C. The flue gases were cooled via an exhaust cooler, heat exchanger and bag filter (BF). Activated carbon and lime were injected in front of BF.

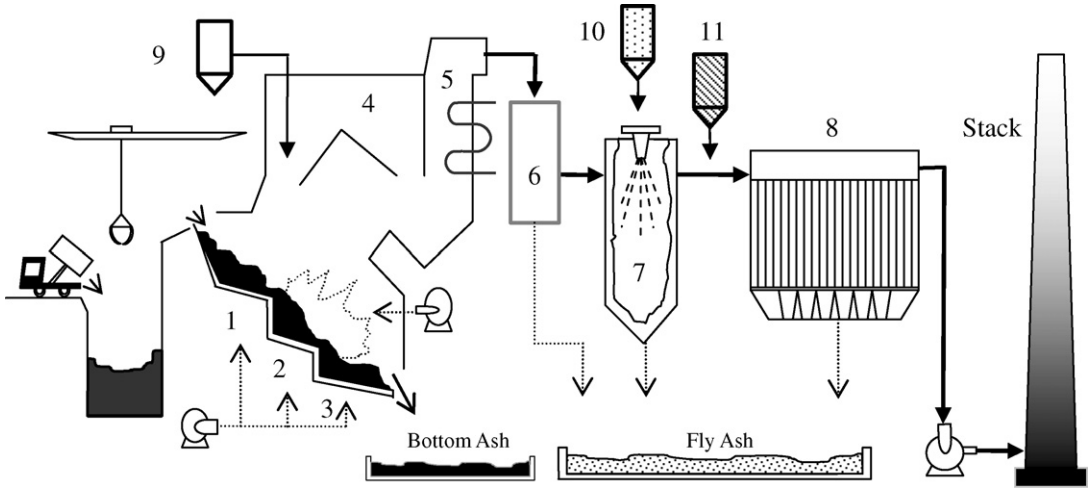

Fig. 2. Schematic diagram of the MSWI-B (mass-burning): (1) first section grate, (2) second section grate, (3) combustion section grate, (4) waste heat boiler, (5) superheater, (6) heat exchanger, (7) semi-dry reactor, (8) bag filter, (9) urea, (10) lime, and (11) activated carbon.

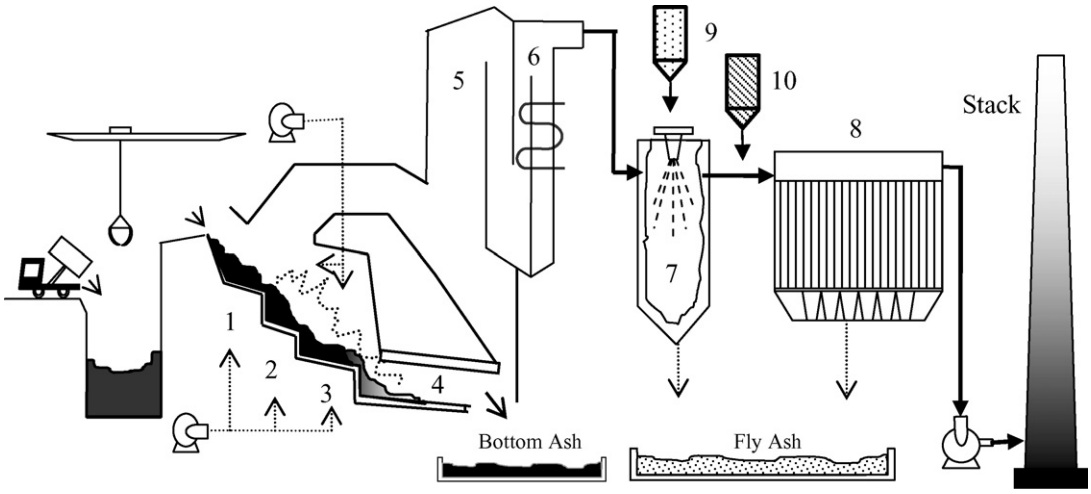

Fig. 3. Schematic diagram of the MSWI-C (mass-burning + rotary kiln): (1) first section grate, (2) second section grate, (3) combustion section grate, (4) rotary kiln, (5) waste heat boiler, (6) heat exchanger, (7) semi-dry reactor, (8) bag filter, (9) lime, and (10) activated carbon.

Incinerator B was mass-burning and with a treatment capacity of 900 tonnes/day. The mass-burning used a three-step movable grate system (involving first, second and combustion section grates). The temperature in the combustion chamber was controlled at 850–1050 °C to complete the combustion, after which urea was added in the chamber to decompose NOx simultaneously. Waste heat boiler and heat exchanger were then installed at the furnace outlet to generate electricity. The flue gases were led through an air pollution control system, comprising a semi-dry scrubber (SD) followed by a BF. MSWI-B removed acid gas from the flue gas using lime slurry, heavy metals and dioxins using activated carbon, and particulates using BF. Fig. 2 illustrates a flow diagram of MSWI-B process.

The incineration system of C consisted of two types, including mass-burning and rotary kiln. Incinerator C has a capacity of 900 tonnes/day and an operating temperature between 850 and 1050 °C. The mass-burning was a three-step movable grate system, and its primary functions were drying, combustion and turbulence, respectively. Unburned materials from mass-burning produced would re-combust in the rotary kiln. The kiln burning process was worked by bringing unburned materials to the surface and into the flame. Following the combustion system, the flue gases were through a waste heat boiler and heat exchanger to generate electric power. The APCDs comprised of a SD and BF. Lime slurry was injected into SD followed by the addition of activated carbon. A schematic diagram of MSWI-C is illustrated as Fig. 3.

Table 2 lists the operating information of three MSWIs. The MSWIs were equipped with different combustion systems and APCDs. MSWI-A differed significantly from B and C owing to not generating electric power and having different APCDs. Although both MSWI-B and C have the same system of mass-burning, BF and SD, additional rotary kiln added to MSWI-C. Therefore, all three MSWIs yield different results in terms of the influence of the ash characteristics. Bottom and fly ashes were sampled in August 2005, and were characterized using the following analytical methods.

2.2. Analytical methods

Bottom and fly ashes from three MSWIs in Taiwan were analyzed, including particle size distribution, morphology, min-

Table 2
General information on MSWI used for sampling

	MSWI-A	MSWI-B	MSWI-C
Furnace type	Fluidized bed	Mass-burning	Mass-burning and Rotary kiln
Capacity (tonnes/day)	95 × 1 unit	450 × 2 unit	300 × 3 unit
Input waste (%)	90% HW[a] + 10% BW[b]	90% HW + 10% BW	90% HW + 10% BW
Furnace temperature (°C)	800–950	850–1050	850–1050
APCDs	BF[c]	SD[d]; BF	SD; BF
Additives	Lime; PAC[e]	Urea; lime; PAC	Lime; PAC
Electric power (kWh/day)	–	∼500	∼400

[a] HW: household waste.
[b] BW: business waste.
[c] BF: bag filter.
[d] SD: semi-dry scrubber.
[e] PAC: powder activated carbon.

eralogical, chemical composition, and heavy metal leaching behavior.

2.2.1. Particle size distribution

The particle size distribution of the ash was segregated into different fractions using a shaker fitted with standard meshes of different sizes. The ash was dried at 105 °C for 24 h. Bottom ashes and fly ashes were sieved into particle size classes of 4, 12, 18, 20, 40, 60, 80 meshes (4750, 1680, 1000, 850, 425, 250 and 180 μm) and 60, 80, 120, 170, 200, 270 meshes (250, 180, 125, 88, 75 and 53 μm), respectively.

2.2.2. Morphology and mineralogical

The morphology of bottom and fly ashes was observed using a scanning electron microscopy (SEM). Moreover, the crystalline minerals present in the ash were identified using X-ray diffraction (XRD). Diffraction patterns were manually analyzed utilizing the joint committee on powder diffraction standards (JCPDS).

2.2.3. Chemical composition

A 1 g dried ash sample was obtained using microwave oven and digested with an acidic solution of $HNO_3/HF/H_3BO_3$. The solution was diluted with 50 mL of distilled water and analyzed by an inductively coupled plasma/mass spectrometry (ICP-MS).

2.2.4. Leaching test of heavy metals

The ash leaching test was carried out according to the Taiwan EPA standard testing method for solid waste. The ash and a leaching solution (CH_3COOH) at a weight/volume ratio of 1/20 were mixed and agitated for 18 h at 30 rpm. The leachate was then filtered. The heavy metal concentration was analyzed by atomic absorption (AA).

3. Results and discussion

3.1. Different particle size distribution of ashes

The mass percentages of the particle size distribution of bottom ashes and fly ashes for three MSWIs are shown in Figs. 4 and 5. Bottom ashes were classified as one of the eight component fractions previously described. As Fig. 4 clearly shows, in all samples of bottom ashes from incinerators A and C, the particles were probably in the range 1680–4750 μm. The over 250 μm size fractions of both MSWIs comprise around 90–95% of the weight of the bottom ash. Bottom ash B in the range of 1680–4750 μm comprises 26.7% of particle size distributions. Notably however, the amounts of bottom ash B which have particle sizes below 180 μm were about 28.5%. This result may relate to the combustion chamber of MSWI-B injecting urea to decompose NOx, and many of these fine particles stick to the surface of the bigger particles. For the transportation and mixing system of three incineration processes, a fluidized bed is a uniform gas–solid system. The gas has provided a good solid mixing between wastes and bed materials. The addition of bed materials inside a fluidized bed provides better heat transfer efficiency and contact probability for wastes treatment. A mass-burning is a movable grate system by mechanical mixture to treat wastes. A rotary kiln is a rotating combustion system that keeps waste moving by a long retention time to achieve better contact between the kiln and the waste. Therefore, three incineration furnaces have different particle size distribution of bottom ashes due to mixing method inside the furnace. Chimenos et al. [12] reported the particle size distribution in the bottom ash from two types of MSWI furnaces. The results indicated that different of particle size distribution from two kinds of incinerator, which should be attributed to greater mechanical grinding in solid transport system inside the furnace. Therefore, according to the result of this study, these differences of the particle size distribution of bottom ashes from three MSWIs probably result from the transportation system (the mixture of solid wastes and air turbulence) inside the incineration furnace.

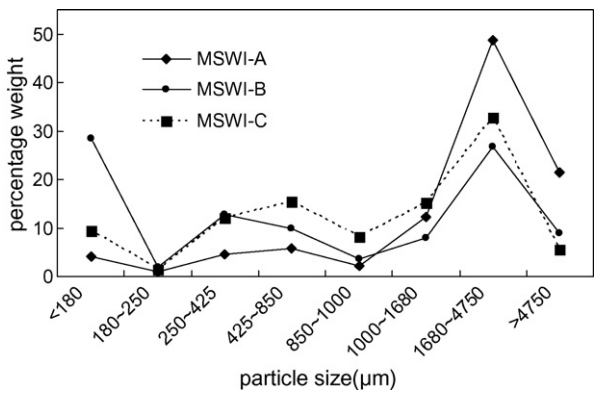

Fig. 4. Particle size distribution in bottom ash from three MSWIs.

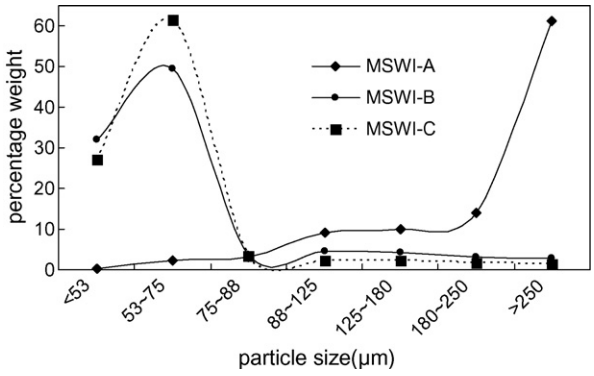

Fig. 5. Particle size distribution in fly ash from three MSWIs.

Previous studies have demonstrated that the particle size distribution of the fly ash probably ranged between 2 and 1000 μm [13]. Furthermore, over 95% of the particle size distributions of fly ashes were smaller than 149 μm [14]. Therefore, this study analyzed fly ashes with a particle size of 53–250 μm. The results are shown in Fig. 5, which indicated that the size distributions of fly ash particles sampled from three MSWIs markedly differ from each other. Fly ash B and C have particle size distributions between 53 and 75 μm are about 49.4% and 61.6% size distributions, respectively. Additionally, the particle size distribution of both incinerators exhibits similar values to Mangialardi et

al. [14]. It is thought that incinerators B and C are different incineration processes, and use the same APCDs to inject lime to control HCl emissions. Additionally, if no appropriate treatment is provided for the fine fly ash of incinerators B and C, secondary pollution may occur. Fly ash from incinerator A was distributed differently to that in incinerators B and C. The particles from incinerator A are larger than the 250 μm size which is about 61.2% size distributions. Meanwhile, just 24.82% of fly ash A is in the range of 53–125 μm. This may result from the use of silica sand as a fluidized material in incineration furnace A, and the particle attrition increased with decreasing average bed material size and the production of large fine particles [11]. These fine particles are directly collected via an exhaust cooler.

3.2. Ash morphology

A morphology observation by SEM (i.e. 5000 times) is conducted to clearly understand and compare different incineration processes affecting the ash surface structure. Fig. 6 shows the SEM photography of the ash of these three MSWIs. Clearly the morphology of the ash is variable and complex as a result of different incineration processes. The surface of bottom ash A has numerous piecemeal materials and irregular particles. Meanwhile the surface of bottom ash B and C contain insignificant hollow spheres on the surface, but bottom ash C is rather smooth. The crystals from the bottom ash of incinerator C are better formed than those of incinerators A and B. Due to an increase in the retention time of solid wastes treatment in the incinera-

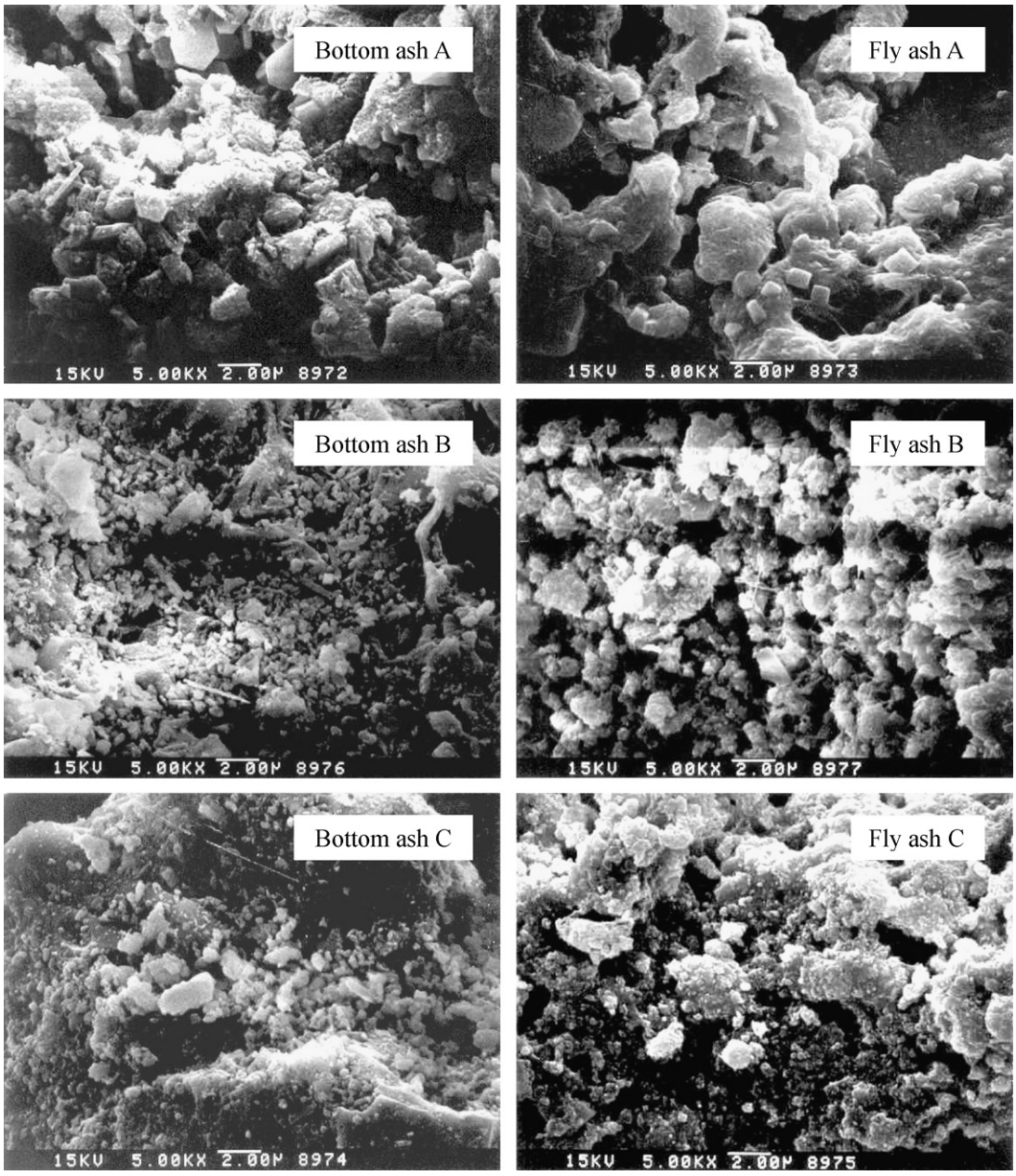

Fig. 6. SEM photographs of ash (5000×).

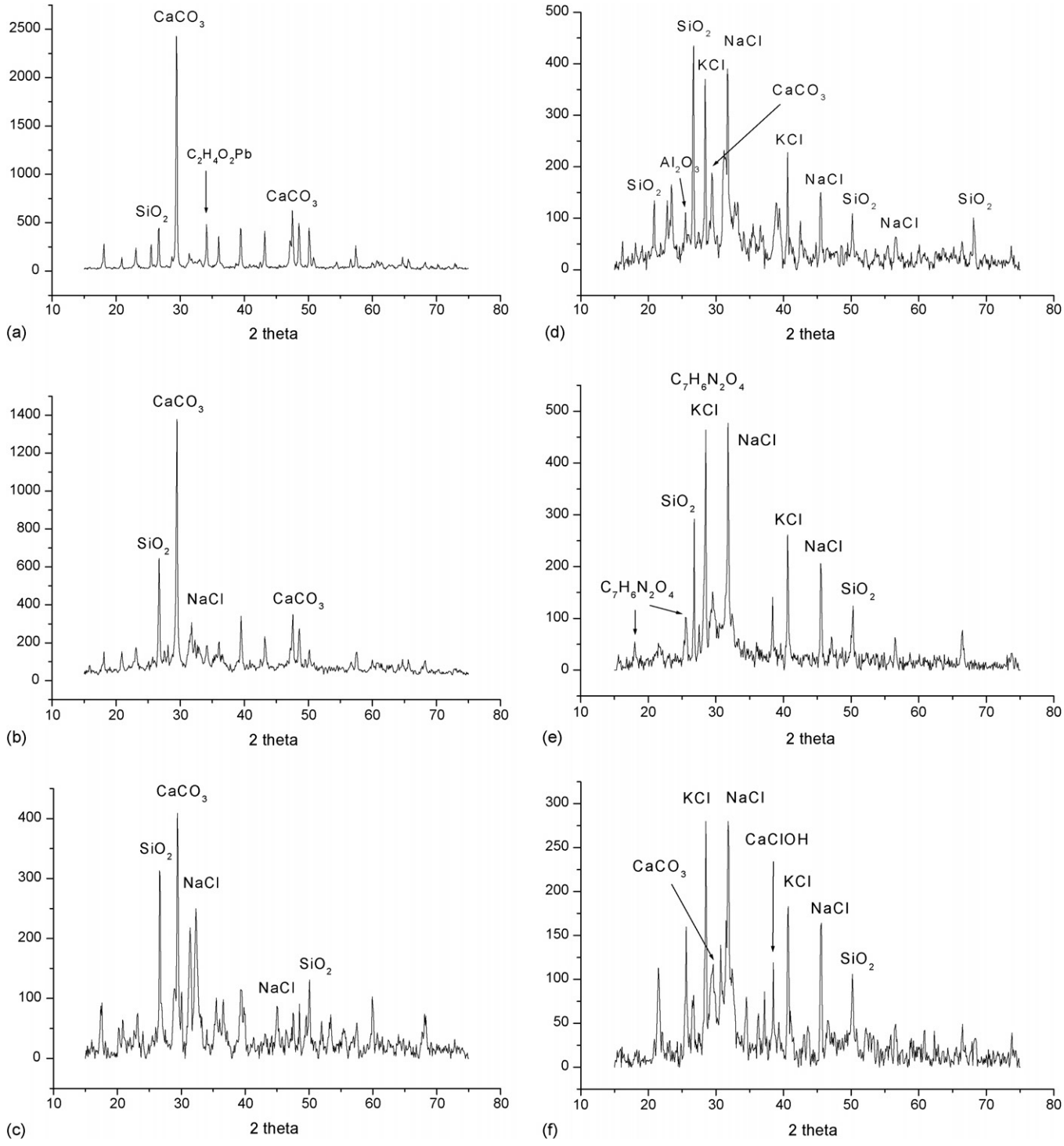

Fig. 7. XRD analysis results: (a) bottom ash A; (b) bottom ash B; (c) bottom ash C; (d) fly ash A; (e) fly ash B; (f) fly ash C.

tion furnace of MSWI-C, which causes an increase in surface agglomerate phenomenon.

Based on the SEM photos, the surface of fly ash A produced smoother agglomerations than bottom ash A. Fly ash B is characterized by a more uniform distribution of concaves and agglomerations on its surface. Furthermore, fly ash C has a fairly smooth surface and few hollow spheres. Fly ash crystals are generally superior to those of the bottom ash, as demonstrated by the irregular shapes and concave surfaces of fly ashes. This phenomenon probably occurs because the fly ash particles generally experience higher temperatures over the pathway in the flue gas stream [5,15]. The influence of the surface of bottom ashes and fly ashes was contributed from bed materials or wastes containing impurities and complex components that may cause the particles to agglomerate at high temperature during combustion. The agglomerate process of incinerator A primarily occurs in the primary and second combustion chambers. MSWI-B forms agglomerate phenomenon from the upside mass-burning bed,

waste heat boiler and heat exchanger. MSWI-C has the same process as MSWI-B, but incinerator C is also linked to a rotary kiln following mass-burning. The high agglomerate products of fly ash C are better formed than those of incinerators A and B due to the furnace type and its longer retention time.

3.3. Mineralogy

XRD is used to determine the composition of the ash from MSWIs. To identify the compositions in the ash samples, these peak positions are determined manually and checked against the JCPDS file. Fig. 7(a)–(c) illustrates the XRD analysis of bottom ashes from three incineration furnaces. The analytical results demonstrate that all bottom ash samples present similar patterns, including $CaCO_3$, SiO_2 and NaCl. Additionally, $C_2H_4O_2Pb$ is observed in bottom ash A (Fig. 7(a)). As shown in Fig. 7(d)–(f), fly ashes have highly complex mineralogy. The complex mineralogy of fly ashes results from several processes, including vaporization, melting, crystallization, vitrification, condensation and precipitation, which occur during the flue gas combustion and treatment [5]. The mainly crystalline compounds of the three fly ashes detected include $CaCO_3$, NaCl, KCl, SiO_2, and so on. Regarding the presence of alkali chlorides, Wang et al. [16] reported that solid wastes contained alkali chlorides, and had stronger reaction activity than other heavy metals. Regardless of organic chloride or inorganic chloride, both were easier to generate NaCl or KCl. XRD analysis of fly ash B (Fig. 7(e)) shows that samples also contain $C_7H_6N_2O_4$. The result can be explained in terms of urea added to the combustion chamber to decompose NOx. Furthermore, N-ion may react to form $C_7H_6N_2O_4$ on the fly ash surface. Fig. 6(c) also shows that the fly ash C contains the species of CaClOH that is caused by injecting lime to the flue gas before BF. Lime is added for absorption of acid, mainly HCl. The result indicated that lime can efficiently remove HCl. The main species are identified by JCPDS including: SiO_2, quartz (JCPDS #33-1161); KCl, Sylvite (JCPDS #41-1476); NaCl, Halite (JCPDS #5-0628); $CaCO_3$, Calcite (JCPDS #5-0586); Al_2O_3, Corundum (JCPDS #10-0173).

3.4. Chemical composition of ashes

Generally, the ash primarily consists of SiO_2, CaO, Al_2O_3, Fe_2O_3, Na_2O and MgO. A microwave and ICP-MS were used to analyze the chemical compositions of the ash. Table 3 lists the analytical results for the ash composition. Comparison of the results reveals that bottom ash A and C comprise of SiO_2 at proportions of 22.904 and 29.490%, respectively. According to chemical composition result, bottom ash A and C comprise of SiO_2 at proportions of 22.904% and 29.490%, respectively. CaO is the second most significant component of bottom ash A (17.833%) and C (18.205%). On the contrary, CaO (18.719%) represents a significant percentage of bottom ash B, which was the same as bottom ash A and C. The characteristic of bottom ashes was mainly affect by two factors, including the composition of input waste and the operating process of incineration furnaces. The chemical composition of bottom ashes was directly affected from input wastes if there was no additive into incineration furnace. Although three incinerators contain the same percentage of input wastes (90% household waste and 10% business waste), but the chemical composition of ashes was not all same. It was difficult to obtain the information of the chemical composition of input waste from three incinerators. However, there was not adding CaO during incineration furnace from A, B and C. Therefore, these results indicate that input waste may affected the chemical composition of the bottom ash from three incinerators.

Table 3
Chemical composition of bottom ash and fly ashes (wt.%)

	MSWI-A		MSWI-B		MSWI-C	
	Bottom ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash
CaO	17.833	12.438	18.719	22.236	18.205	17.403
SiO_2	22.904	22.082	2.250	0.130	29.490	6.736
Al_2O_3	0.185	1.549	1.143	1.196	2.673	0.145
Fe_2O_3	11.397	6.773	9.054	0.809	17.077	0.511
Na_2O	3.688	7.162	4.461	8.753	6.084	8.208
MgO	1.048	1.279	1.202	0.782	1.391	0.815

The analytical results for fly ash A reveal that SiO_2 is the largest component, followed by CaO and Na_2O, with levels are 22.082, 12.438, and 7.162%, respectively. Although APCDs of incinerator A is injected lime, SiO_2 constitutes the major part of fly ash A. The chemical compositions of fly ash B and C are dominated by CaO and Na_2O. There is a high level of CaO in fly ash of B and C due to the injection a lime solution for removing acid gas. Comparing the chemical composition of the three incinerators, levels of SiO_2, Al_2O_3, Fe_2O_3 and MgO in fly ash from fluidized bed incinerators are confirmed to be higher than those from mass-burning or mass-burning linked rotary kiln incinerators. Especially, Table 3 shows that fly ash A has much higher levels of SiO_2 than fly ash B and C. Generally, SiO_2 was

Table 4
Leaching concentration of heavy metals from three MSWIs (mg/L)

	MSWI-A		MSWI-B		MSWI-C		Taiwan limit
	Bottom ash	Fly ash	Bottom ash	Fly ash	Bottom ash	Fly ash	
Cu	0.048 ± 0.009	0.048 ± 0.010	3.237 ± 0.115	1.940 ± 0.192	0.272 ± 0.091	1.353 ± 0.249	15
Pb	0.374 ± 0.119	0.449 ± 0.085	0.441 ± 0.044	73.253 ± 1.335	0.364 ± 0.019	79.693 ± 3.323	5
Cr	1.747 ± 0.098	0.149 ± 0.010	0.825 ± 0.062	0.398 ± 0.034	0.087 ± 0.021	0.525 ± 0.003	5
Cd	0.050 ± 0.005	0.092 ± 0.007	0.054 ± 0.006	0.174 ± 0.003	0.047 ± 0.006	0.159 ± 0.006	1

Level is average ± standard deviation.

a major component of the bottom ash [17]. This results probably because the small particles of SiO_2 from the bed materials (quartz) of fluidized bed blow to the APCDs. The composition of fly ashes may be influenced by type of incineration furnace, input waste, and the injection of additives into the APCDs.

3.5. Leaching concentration of heavy metals from ashes

TCLP is one of the Federal EPA test methods that are used to characterize waste as either hazardous or non-hazardous for the purpose of disposal. Table 4 lists the result of TCLP analysis for the ash from different incineration processes. Three replicates are prepared to meet the QA/QC requirements that generated the data ranges in Table 4. The leaching concentration of heavy metals in the three bottom ashes clearly corresponds to the regulatory level. Therefore, these bottom ashes are not considered a hazardous waste. However, fly ash B and C are considered hazardous wastes because of the leaching concentrations of Pb exceeding the regulatory level. The values are 73.253 and 79.693 mg/L, and correspond to the limit of Pb for fly ash B and C, respectively. The results of this study show that fly ash B and C require further treatment before final disposal. Specifically, the leaching concentrations of heavy metals from fly ash A are all significant below the regulatory level, and also the levels for fly ash B and C, and thus the ash can be landfilled directly. Wey et al. [8] indicated that the silica bed of fluidized bed adsorbs high proportions of heavy metals (Pb, Cr and Cd). Therefore, a fluidized bed incinerator appears quite suitable for retaining metals during incineration.

Generally, the volatilization of heavy metals in incineration systems depends on their physical and chemical properties, such as saturated vapor pressure and boiling point. Additionally, levels of Pb and Cd in fly ashes from three incinerators were confirmed to be higher than those bottom ashes (Table 4). The effect of furnace temperature from MSWI-B and MSWI-C for Pb and Cd is more significant than for MSWI-A in the range 850–1050 °C. Additionally, volatile metals such as Pb and Cd are expected to have higher transfer rates to the fly ash with increasing furnace temperature. Cu and Cr have higher boiling points and are relatively stable species which remain in the bottom ash. However, the leaching concentration of Cu in fly ashes is higher than that in bottom ashes from MSWI-A and MSWI-C with the exception of MSWI-B. This phenomenon may occur because some of the metals found in fly ashes are result from particulate matter carried over from the furnace in the flue gas [13].

4. Conclusion

This work studied the characteristics of bottom and fly ashes from three MSWIs in Taiwan. The MSWIs were chosen based on different incineration furnaces, namely fluidized bed, mass-burning and mass-burning links rotary kiln, respectively. The particle size distribution, morphology, mineralogical, chemical composition and leaching behavior of heavy metals from ash samples were assessed to compare the characteristics of ashes from three types of MSWIs.

Comparing the analytical data regarding the properties of bottom ashes and fly ashes, reveals that three types of incineration processes significantly differ. The results revealed that three types of incineration processes have different characteristic for ashes due to transportation and mixing system inside furnace. Based on the results of this study, we conclude the following.

1. The bottom ash from MSWI-B had 28.5% particle size distributions below 180 μm. Fly ash B and C displayed similar value to previous studies indicating that have been indicated over 95% of fly ash particles have sizes smaller than 149 μm. 61.2% of fly ash A have larger than the 250 μm.
2. A morphology observation by SEM clearly found that ashes from three MSWIs have the different surface structures because of agglomerate process.
3. The major of components of ashes from the three MSWIs were $CaCO_3$, SiO_2 and NaCl. XRD analysis of fly ash B demonstrated that the samples also contain $C_7H_6N_2O_4$ which could be explained in terms of urea being added to the combustion chamber to decompose NOx into lead to form in the surface of fly ashes.
4. Comparing the chemical composition of three MSWIs, bottom ash A and C comprise SiO_2, but CaO was found in large percentage in bottom ash B. Levels of SiO_2, Al_2O_3, Fe_2O_3 and MgO in fly ash A were higher than those from fly ash B and C. Particularly, fly ash A was significantly higher levels of SiO_2 than fly ash B and C.
5. The leaching concentration of heavy metals from fly ash A (fluidized bed incinerator) was lower than that from fly ash B and C. Fly ash A can be landfilled directly because of corresponding to the regulatory level. The fluidized bed incineration process appears a potential for handling and retaining heavy metals for ashes. The result was also provided the valuable information for incinerator design and operation.

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