



Melting of municipal solid waste incinerator fly ash by waste-derived thermite reaction

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ABSTRACT

This work describes a novel approach for melting municipal solid waste incinerator (MSWI) fly ash, based on self-propagating reactions, by using energy-efficient simulated waste-derived thermite. The self-propagating characteristics, the properties of the recycled alloy and slag and the partitioning of heavy metals during the process are also studied. Experimental results demonstrate that the mix ratio of fly ash to the starting mixture of less than 30% supports the development of the self-propagating reaction with a melting temperature of 1350–2200 °C. Furthermore, metallic iron (or alloy) and the slag were retrieved after activation of the thermite reactions among the starting mixtures. It was noted that more than 91 wt.% of iron was retrieved as alloy and the rest of non-reductive oxides as slag. During the thermite reactions, the partition of heavy metals to the SFA and flue gas varied with the characteristics of the target metals: Cd was mainly partitioned to flue gas (75–82%), and partition slightly increased with the increasing fly ash ratio; Pb and Zn, were mainly partitioned to the SFA, and the partition increased with increasing fly ash ratio; Cu was partitioned to the SFA (18–31%) and was not found in the flue gas; and moreover stable Cr and Ni were not identified in both the SFA and flue gas. On the other hand, the determined TCLP leaching concentrations were all well within the current regulatory thresholds, despite the various FA ratios. This suggests that the vitrified fly ash samples were environmental safe in heavy metal leaching. The results of this study suggested that melting of municipal solid waste incinerator fly ash by waste-derived thermite reactions was a feasible approach not only energy-beneficial but also environmental-safe.

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1. Introduction

During the formation of a sustainable resource recycling-oriented society, two problems are of increasing concern—the disposal of waste materials and the declining availability of natural resources use as raw and construction materials, such as aggregates and cement. The need to counter the excessive depletion of natural resources and to dispose properly the considerable amount of residual wastes (sludge, incinerator ash and sediments) provides an excellent opportunity to recycle the residual wastes into construction materials. Doing so fills and closes the environmental recycling loop, promoting sustainability.

Inorganic residual wastes are currently melted to recycle slag as fine and/or coarse aggregates [1–4]. This practice suffers from being energy-intensive, regardless of whether the energy source is gas, coal or electricity (including plasma) [5]. Furthermore, the required

melting facilities are complex and require greater operational skills [4]. Accordingly, a novel melting method is sought that is simple in design and operation, involves small equipment, has few emissions, is operationally efficient and energy-saving, environmentally sound and also recycling-beneficial. Accordingly, this investigation elucidates the feasibility of melting municipal solid waste incinerator (MSWI) fly ash (referred to as FA) using the exothermal energy that is generated in thermite reactions among the wastes. This approach also has the advantage of recovering metals as a secondary material and slag for use as a construction material.

Thermite reactions are a sort of highly exothermic reactions that are involved in the reduction of a metallic or a non-metallic oxide by a metal to form more stable products [6]. These reactions are highly exothermic heat and self-propagating, and have thus been adopted extensively in material synthesis, and recently to solve environmental problems, such as the fixation and consolidation of high-level radioactive wastes [7,8], the treatment and recycling of highly toxic solid wastes from electrolytic zinc plants [9–11] and the recycling of by-products from the steel industry [12]. The typical thermite reaction between aluminum (Al) and iron(III) oxide

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releases 558.6 kJ/mole oxygen [13]. Aluminum also reacts with zinc oxide and cupric oxide to generate 350.5 and 3161.9 kJ/mole oxygen [13], respectively. This very large energy is most frequently adopted to melt refractory residual wastes, such as MSWI fly ash, to promote the recycling of metal and slag. This process is particularly attractive when thermite reactants are obtained from industrial wastes and/or by-products. For example, iron(III) oxide may be found in oxide dust and the byproducts from steel making plants or surface treatment processes, zinc oxide from smelting operations, and aluminum in aluminum dross from aluminum refining plants [14]. These thermite-containing wastes represent an outstanding opportunity to treat waste with wastes, and in an efficient, energy-saving and recycling-promoting manner.

However, in the melting of MSWI fly ash by thermite energy, the characteristics of the thermite reactants and the mixing ratio of the fly ash to the total mix (thermite and fly ash) dominate the melting temperature due to endothermic effects of the non-reactive oxides/metals and excessive reactive metals. These factors will, therefore, determine the melting temperature, the characteristics of the recycled slag and alloy, and also the partitioning behavior of heavy metals during the melting process [15,16]. Additionally, the complexity and inhomogeneity of the MSWI fly ash further complicates this process [17]. Consequently, a feasibility study of the melting of MSWI fly ash using waste-derived thermite is desired for the design and implementation of a novel melting process.

This work investigated a novel approach for melting the municipal incinerator fly ash by using thermite. The self-propagating characteristics, the properties of the recycled alloy and slag and the partitioning of heavy metals during the process are also studied.

2. Materials and methods

2.1. Fly ash

The fly ash used in this study was collected from a mass-burning type of municipal solid waste (MSW) incinerator located in the northern part of Taiwan, with a processing capacity of 1350 tons of local municipal wastes per day. The tested ash was a mixture, comprised of stoker boiler ash, cyclone ash (lime-reacted), and bag filter ash. Approximately 50 kg of fly ash was collected from the MSW incinerator fly ash silo where boiler ash, cyclone ash and bag filter ash were dumped. The mixed ash is referred to as fly ash, and may contain as much as 40% of CaO. The composition listed in Table 1 shows the fly ash used in this study is typical [18]. The fly ash was oven-dried at 100 °C overnight before testing. The chemical composition of the tested fly ash is shown in Table 1.

Table 1
Chemical composition of MSWI fly ash used

Species	Content (wt.%)
CaO	39.68
SiO ₂	10.69
Al ₂ O ₃	4.14
Fe ₂ O ₃	1.56
MgO	1.45
Na ₂ O	0.93
K ₂ O	2.96
SO ₃	5.13
TiO ₂	<0.1
Cr ₂ O ₃	0.1
MnO	0.1
CuO	0.1
CdO	0.1

Table 2

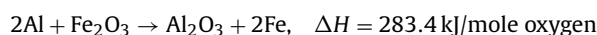
Composition of the aluminum and iron(III) oxide used for the thermite melting reaction

Species	Aluminum powder	Iron(III)oxide powder
Al (%)	>93	–
Fe (%)	<0.5	>67.9
Pb (mg/kg)	10.05	5.25
Cd (mg/kg)	2.05	1.75
Cr (mg/kg)	205	N.D.
Cu (mg/kg)	8	4.95
Zn (mg/kg)	25	18
Ni (mg/kg) ^a	350	N.D.

^a Ni <0.016 mg/kg.

2.2. Simulated thermite

The simulated thermite used in this study was typical of one prepared by mixing industrial aluminum and iron oxide powder stoichiometrically according to the following reaction:



The composition of the aluminum and iron(III) oxide is shown in Table 2. Impurities in the industrial aluminum powder contributed 205 mg/kg to the chromium and 350 mg/kg to the nickel content of the starting mixture, whereas Fe₂O₃ of 97 wt.% purity contributed 67.9 wt.% to the Fe content.

2.3. Experimental apparatus

The thermite melting apparatus was composed of a crucible reactor, an enlarged upper part and a chimney, as shown in Fig. 1. The reactor and the enlargement were made of graphite and the chimney of aluminum oxide. The reactor had an inner diameter of 4 cm and a depth of 10.5 cm. Temperature sensors were embedded in the upper free board to determine and to estimate the reaction temperature at the surface of the mixture. The apparatus was enclosed by an outer tank which was connected to a filter, a volume flow meter and a train of sampling impingers for secondary melting fly ash and gas sampling. The sampling train consisted of a series of six impingers following the filter. Multiple heavy metals and their compounds in the flue gases were trapped by using a modified USEPA method 5 (MM 5 method). Accordingly, the first impinger was left empty, while the second and third impingers were filled with a combined solution of 5% HNO₃ and 10% H₂O₂ for trapping most of the heavy metals and their compounds in the combustion gases. The fourth and fifth impingers were filled with 4% KMnO₄ and 10% H₂SO₄ to capture the mercury emissions. The final impinger was filled with silica gel to remove the moisture content from the gases.

2.4. Experimental operation

The reaction temperature of the melting process involving waste-derived thermite is governed by the weight ratio of the fly ash to the starting mixture (i.e., thermite mixed with fly ash), referred to as the fly ash ratio, or the FA ratio. In this work, the FA ratio was varied from 5 to 40 wt.%, at an 5 wt.% increment. The tested thermite was first prepared by stoichiometrically mixing industrial aluminum powder with and iron oxide powder. The prepared thermite was then mixed with fly ash at the aforementioned FA ratios. Finally, the starting mixture (thermite and fly ash) was packed into the graphite reactor and ignited with an electrically heated wire to initiate the thermite reaction. The reaction temperature was recorded by embedded sensors as the thermite reaction proceeded. The secondary fly ash (referred to as the fly ash gen-

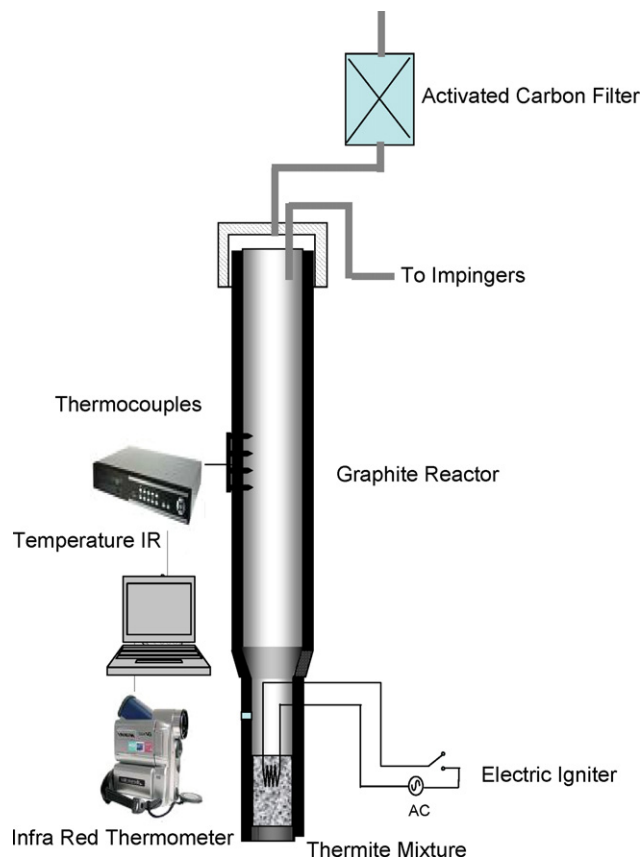


Fig. 1. Schematic representation of experimental set-up.

erated from the melting process) was collected by a filter and the off-gas was trapped by impingers during and after the occurrence of the thermite reaction. After the completion of the reaction, the resultant slag and alloy were collected for subsequent analyses.

2.5. Laboratory analyses

The melting temperature was estimated by the regression of the temperature measured by the embedded sensors above the molten mixture. The slag and alloy were collected and characterized, including their speciation by X-ray diffraction (XRD) techniques, major element, heavy metal partitioning and Toxic characteristic leaching procedure (TCLP) leaching concentration by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) analysis. The XRD analyses were carried out by a Siemens D-5000X-ray diffractometer with Cu K α radiation and 2θ scanning, ranging between 5° and 70° . The XRD scans were run at 0.05° steps, with a 1 s counting time. The extraction procedure requires the preliminary evaluation of the pH characteristic of the sample to determine

the proper extraction fluid necessary for the experiment. Upon testing, extraction fluid #B (pH 2.88 ± 0.05) was used for the TCLP analysis. This fluid was prepared by adding 5.7 mL acetic acid to 500 mL double distilled water, and diluting to a volume of 1 L. A 25-g sample was placed in a 1-L Erlenmeyer flask, and a 500-mL extraction fluid was added to each Erlenmeyer flask. These samples were agitated for 18 h using an electric vibrator. The extraction fluid was filtered by 6–8 μm pore size Millipore filter paper. The leachates were preserved in 2% HNO $_3$. 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 (HF:HClO $_4$:HNO $_3$ = 2:1:1). The recovery rates, defined as the ratio of the input mass to the output mass, were evaluated for retrieved slag and alloy, respectively, on the basis of control group (T00, without the addition of fly ash).

3. Results and discussion

3.1. The reaction temperature

The MSWI fly ash tested in this study is comprised of a mixture of lime-reacted cyclone ash, boiler ash and bag filter ash. It is characterized by its higher melting point and difficult to melt without modifying its composition or increasing the melting temperature. By using thermite energy to melt such fly ash, the thermite-fly ash ratio will eventually govern the reaction temperature, and thus the quality of the recovered slag. Table 3 shows the self-propagating behavior and reaction temperature of the mixtures.

It is evident from Table 3 that the reaction became self-propagating and self-sustained at various FA ratios equal to or less than 30 wt.%. The corresponding reaction temperature, ranging from 1350 °C to 2200 °C, was found to have a significant negative correlation ($R^2 = 0.95$) with the FA ratio. The activation of the tested thermite mixture containing 0–40% fly ash showed that self-propagation of the reaction prevailed at a fly ash ratio less than 30%. Since the addition of fly ash might provide with melting aids such as MgO, Na $_2$ O, and K $_2$ O, it is possible for the tested mixture of fly ashes to melt at 1350 °C. The observation of the macrostructure, and the extremely low leaching concentrations could confirm the melting occurred at 1350 °C while the reaction self-propagated in this study.

3.2. Application of thermite-type reactions

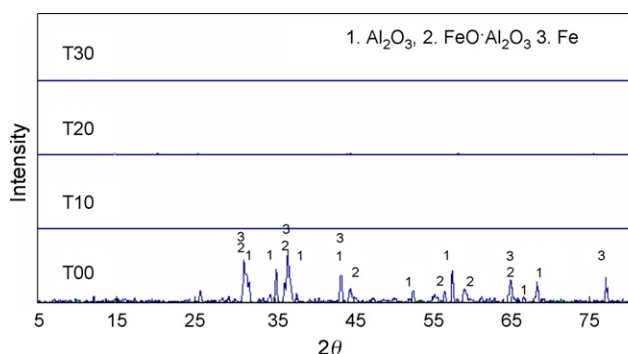
Aluminum and iron oxide functioned as the hypergolic fuel for the MSWI fly ash melting process. For industrial practice, wastes and/or their byproducts would be used, such as aluminum dross from aluminum foundries and iron oxides from the fly ash and byproducts of steelworks. The reactants, aluminum and iron oxide, were mixed stoichiometrically, resulting in a typical thermite reaction to be tested as a fuel source. Subsequently, the MSWI fly ash was mixed with the previous thermite to form a starting

Table 3
Reaction behavior and reaction temperature of the mixtures investigated

Test No.	FA ratio (wt.%)	Self-propagation	Reaction temperature (°C)	Adiabatic temperature (°C)
T00	0	Yes	2200	3046
T05	5	Yes	1970	2881
T10	10	Yes	1770	2715
T15	25	Yes	1720	2550
T20	30	Yes	1450	2384
T25	25	Yes	1340	2218
T30	30	Yes	1350	2053
T35	35	No	–	–
T40	40	No	–	–

Table 4
Combinations of the starting mixture and the recovered slag and alloy

Test no.	Input (g)				Recovered (g)		Recovery rate (%)	
	Mixture	Al	Fe ₂ O ₃	Fly ash	Slag	Alloy	Slag	Alloy
T00	80.0	20	60	0.0	38.8	42.0	–	–
T05	84.2	20	60	4.2	46.1	38.1	109.2	90.7
T10	88.9	20	60	8.9	50.7	38.3	108.0	91.1
T15	94.1	20	60	14.1	53.9	40.2	103.4	95.7
T20	100.0	20	60	20.0	61.6	38.4	106.2	91.4
T25	106.7	20	60	26.7	67.7	38.3	105.8	91.2
T30	114.3	20	60	34.3	68.7	45.5	95.2	108.2

**Fig. 2.** XRD results of the slag from simulated waste-derived thermite reaction with different FA ratio.

mixture at a FA ratio ranging from 0 to 30 wt.%. The starting mixture and the recovered slag and alloy after reaction are shown in Table 4.

It was noted that the recovered amount of the slag increased as the FA ratio increased. The alloy, mainly iron, was 91–108 wt.% recovered. In self-propagating batches (i.e., an FA ratio not greater than 30%), it was found that there was no significant difference between the amounts of recovered alloy, as compared to the iron calculated stoichiometrically, implying that the recovered alloy was mainly metallic iron. On the other hand, most part of the vitrified slag was amorphous. However, a small fraction of metallic iron partitioned to the slag was identified as FeO·Al₂O₃ and Al₂O₃, as shown as shown on the XRD patterns in Fig. 2.

As the experiments were conducted with equal amounts of thermite (80 g in this study) and with increasing FA ratios ranging from 0% to 30%, the self-propagating temperature decreased from 2200

to 1350 °C. However, within this range, both the closure of the slag and the alloy showed no significant difference, suggesting that the addition of fly ash increased the slag recovery rate but contributed less to the recovery of the alloy, due to the insignificant amount of metallic oxides contained.

3.3. Distribution of major elements

It is interesting to note that when aluminum and thermite reaction was used as a reducing agent and an energy source for melting process, respectively. The iron was totally recovered from the thermite, as well as a small fraction from the MSWI fly ash. Moreover, other metallic oxides of insignificant amount, except for iron oxide, such as Cr₂O₃, MnO, CuO, and CdO might also be reduced and recovered from the fly ash. The distribution of the major elements and their recovery rates are shown in Table 5.

The major elements in thermite are iron and aluminum, whereas those in MSWI fly ash are aluminum, calcium and silicon. As expected, it was found that most of the iron in the simulated thermite was recovered into alloy; and the aluminum into slag and/or secondary fly ash generated from the melting process (referred to as SFA). The distribution of aluminum to the SFA increased as the FA ratio decreased, indicating that a more violent thermite reaction occurred with a smaller FA ratio. The violent reaction enhanced the spattering of the products, resulting in an increased entrainment of the amount of aluminum oxide collected in the SFA. Calcium and silicon in MSWI fly ash were present as calcium oxide and silicon oxide, and were therefore both retained in the slag.

The generation of the products, i.e., metallic iron, Al₂O₃ and FeO·Al₂O₃, as identified by XRD analysis, were compared to the chemical species in final products as predicted by Roberto Orrù et al. [18].

Table 5
Mass balance and distribution of major elements during thermite type melting

Element	Test No.	Initial Element (g)	Elemental Product (g)				Elemental Distribution (%)				Closure (%)
			Slag	Alloy	SFA	Gas	Slag	Alloy	SFA	Gas	
Al	T00	18.6	0.3	0.04	12.62	0.00	1.8	0.2	67.8	0.0	69.9
	T10	18.7	3.4	1.32	9.41	0.04	18.3	7.0	50.1	0.2	75.6
	T20	18.8	8.7	0.44	4.78	0.09	45.4	2.3	25.1	0.5	73.3
	T30	18.9	15.2	0.40	1.32	0.00	78.3	2.1	6.8	0.0	87.2
Fe	T00	40.3	1.8	26.7	0.1	1.5	4.5	66.3	0.2	3.7	74.7
	T10	40.4	7.5	12.3	1.9	2.2	18.5	30.5	4.7	5.5	59.1
	T20	40.5	13.4	20.9	1.0	0.7	33.1	51.6	2.5	1.7	88.9
	T30	40.6	23.4	7.7	0.5	0.2	57.7	19.0	1.2	0.4	78.2
Ca	T00	6.7	0.01	–	0.01	0.00	0.2	0.0	0.1	0.1	–
	T10	5.5	2.22	0.00	0.15	0.06	40.1	0.0	2.7	1.2	43.9
	T20	10.8	5.40	0.00	0.11	0.09	49.9	0.0	1.1	0.8	51.8
	T30	11.9	9.42	0.00	0.11	0.04	78.9	0.0	0.9	0.4	80.2
Si	T00	0.00	0.02	0.10	0.03	0.01	0.0	0.0	0.0	0.0	–
	T10	0.44	0.27	0.07	0.06	0.04	60.3	16.5	12.5	8.8	98.0
	T20	1.00	0.69	0.03	0.08	0.02	68.9	2.6	7.9	2.5	82.0
	T30	1.71	1.54	0.00	0.06	0.03	90.0	0.1	3.7	1.9	95.7

Table 6
Mass balance and distribution of heavy metals during thermite process

Heavy metals	Test no.	Initial elements (mg)	Elemental product (mg)				Elemental distribution (%)				Closure (%)
			Slag	Alloy	SFA	Gas	Slag	Alloy	SFA	Gas	
Pb	T10	43.46	1.38	0.65	30.17	5.37	3.2	1.5	69.4	12.3	86.5
	T20	97.40	2.93	0.84	67.65	12.28	3.0	0.9	69.5	12.6	85.9
	T30	166.90	7.70	0.45	122.89	21.43	4.6	0.3	73.6	12.8	91.4
Cd	T10	1.47	0.29	0.00	0.05	1.10	20.0	0.0	3.5	75.2	98.8
	T20	3.24	0.66	0.00	0.05	2.60	20.3	0.0	1.6	80.2	102.2
	T30	5.53	1.03	0.00	0.05	4.55	18.6	0.0	0.9	82.3	101.8
Cr	T10	7.50	0.01	7.36	0.00	0.00	0.2	98.1	0.00	0.00	98.3
	T20	11.61	2.57	8.39	0.00	0.00	22.1	72.3	0.00	0.00	94.4
	T30	16.90	14.71	1.74	0.00	0.00	87.1	10.3	0.00	0.00	97.4
Cu	T10	14.40	2.35	4.77	4.44	0.00	16.3	33.1	30.9	0.0	80.3
	T20	32.16	7.77	14.79	5.93	0.00	24.2	46.0	18.4	0.0	88.6
	T30	55.04	33.73	10.79	14.42	0.00	61.3	19.6	26.2	0.0	107.1
Zn	T10	134.30	16.49	0.16	74.40	12.83	12.3	0.1	55.4	9.6	77.4
	T20	300.80	42.46	0.66	225.40	21.06	14.1	0.2	74.9	7.0	96.3
	T30	515.30	77.47	0.09	386.10	42.79	15.0	0.0	74.9	8.3	98.3
Ni	T10	8.79	3.67	1.87	0.00	0.00	41.7	21.3	0.0	0.0	63.0
	T20	9.68	4.34	3.79	0.00	0.00	44.9	39.1	0.0	0.0	84.0
	T30	10.82	5.63	2.38	0.00	0.00	52.0	22.0	0.0	0.0	74.0

3.4. Partitioning behavior of heavy metals

The heavy metals in the waste-derived thermite and in the MSWI fly ash are either incorporated in the vitrified residue and/or the alloy product, or separated from the residue (by evaporation or by different densities of the melted constituents) during the melting process. Obviously, the inherent safety of the slag product is achieved if the heavy metals are extracted quantitatively from slag. The recovered heavy metal compounds themselves can be reutilized as raw materials in metallurgical processes. However the partitioning behavior of the heavy metals during thermite-type melting is of concern. This offers a possibility of combining the separation of the heavy metals either with vitrification of the residues or with the formation of the alloy, as summarized in Table 6.

The volatility of cadmium and lead increased as the melting temperature increased. In this study, the self-propagating temperature of melting ranging from 1350 to 2200 °C at an FA ratio from 0 wt.% to 30 wt.%, it was found that volatile Pb was partitioned 69–74% to the secondary fly ash obtained from the melting process and 12.3–12.8% to the exit gas. On the other hand, volatile Cd was 1–3.5% partitioned to the secondary fly ash, and 75–82% to the flue gas. Zinc was partitioned 55–75% to the fly ash, with only 12–15% to the slag. Metals with refractory volatility such as chromium and nickel were partitioned mainly to the products (slag and alloy), ranging from 94–98% for chromium and 63–84% for nickel. Cop-

per was partitioned mostly between the slag, the alloy and the fly ash. 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 [19]. All these partitioning behaviors were governed by the volatility of the targeted metals and the melting temperature determined by the mix ratio of fly ash.

3.5. Stability of recovered slag

The recovered slag became vitrified and stable in structure, immobilizing the targeted heavy metals. The slag was subjected to the analysis of the total concentrations and the TCLP testing of the targeted metals, as shown in Table 7.

It is noted that the total concentration of targeted heavy metals in the recovered slag samples increased in proportion with increasing FA ratio, indicating that most of the total heavy metal concentrations were contributed to by the MSWI fly ash. On the other hand, the determined TCLP leaching concentrations were all well within the current regulatory thresholds, despite the various FA ratios. This suggests that the vitrified fly ash samples were environmental safe in heavy metal leaching.

Furthermore, the partition characteristics of heavy metals to the SFA and flue gas could be classified into four categories: (1) Cd was mainly partitioned to flue gas (75–82%), and partition slightly increased with the increasing fly ash ratio. (2) Pb and Zn, were

Table 7
TCLP results and heavy metal content for the slags

Test No.	TCLP (mg/L)					Heavy metals in slag (mg/kg)					
	Pb	Cd	Cr	Cu	Zn	Pb	Cd	Cr	Cu	Zn	Ni
Fly ash	93.30	0.29	4.61	1.19	144.21						
T0	–	–	–	–	–	N.D.	0.2	N.D.	N.D.	22.0	3.5
T5	N.D.	0.23	N.D.	0.72	4.15	15.0	3.3	158.0	81.0	200.5	24.0
T10	1.06	N.D.	N.D.	N.D.	6.30	50.0	5.5	143.5	59.0	190.0	57.0
T15	0.38	0.74	N.D.	2.86	5.00	34.0	10.0	154.0	315.0	270.0	37.5
T20	0.47	0.08	N.D.	N.D.	5.60	44.5	13.5	154.9	217.0	298.0	49.5
T25	0.26	0.66	N.D.	0.46	7.96	95.0	19.8	209.5	276.5	368.0	55.0
T30	0.47	0.70	N.D.	0.26	7.50	90.0	23.2	176.0	341.5	300.0	71.5
Regulatory limit ^a	5.0	1.0	5.0	15.0	–						

Detection limit: Pb < 0.016 mg/L; Cd < 0.014 mg/L; Cr < 0.016 mg/L; Cu < 0.015 mg/L.

^a Maximum allowable concentrations according to the EPA regulations.

mainly partitioned to the SFA, and the partition increased with increasing fly ash ratio. (3) Cu was partitioned to the SFA (18–31%) and was not found in the flue gas. (4) Stable Cr and Ni were not identified in both the SFA and flue gas.

4. Conclusions

A novel approach for melting of MSWI fly ash using simulated waste-derived thermite was investigated. The results of this study demonstrated that a FA ratio of up to 30 wt.% allowed the self-propagating characteristics of the reactions, reaching a reaction temperature ranging from 2200 °C to 1350 °C. After the thermite reactions, more than 91 wt.% of iron was retrieved as alloy and the rest non-reactive oxides as slag.

During the thermite reactions, the partition of heavy metals varied types of heavy metals and the incorporated fly ash ratio. It was noted that Cd was mainly partitioned to flue gas (75–82%), and partition increased slightly with the increasing fly ash ratio; Pb and Zn, were mainly partitioned to the SFA, and the partition increased with increasing fly ash ratio; Cu was partitioned to the SFA (18–31%) and was not found in the flue gas; stable Cr and Ni, however, were not identified in both the SFA and flue gas.

On the other hand, the determined TCLP leaching concentrations were all within the regulatory thresholds, despite the various FA ratios. This implied the environmental safety of slag in heavy metal leaching. The results of this work suggested that the melting of municipal solid waste incinerator fly ash by waste-derived thermite reactions was a promising approach both energy-beneficial and environmental-safe.

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