

# Behaviour of municipal solid waste incinerator flyash. I: General leaching study

Y. Gong and D.W. Kirk\*

*Department of Chemical Engineering and Applied Chemistry, University of Toronto,  
200 College St., Toronto, Ontario M5S 1A4 (Canada)*

(Received December 10, 1992; accepted in revised form August 15, 1993)

## Abstract

The understanding of the leaching behaviour of municipal solid waste (MSW) incinerator flyash is important from the environmental point of view, particularly for landfill disposal and also for hazardous metal detoxification or for metal recovery. In this paper, the leachability of metals from MSW flyash was compared for various solvents, including H<sub>2</sub>O, NaOH, HCl, H<sub>2</sub>SO<sub>4</sub>, HClO<sub>4</sub>, HNO<sub>3</sub> and HAc. Hydrochloric acid was found to be a most effective solvent to remove heavy metals from flyash. The experiments with HCl concentrations from 0 to 6 M showed that HCl concentration does not affect the leachability of most elements above 0.5 M HCl. For lead and copper, leachability increases up to 1 M HCl, while for iron leachability increases with increasing HCl concentration through the whole concentration range tested. Silica gel was found to form quickly in concentrated HCl solutions, and caused poor solution filterability. The HCl-leached residue was shown to be non-hazardous.

---

## 1. Introduction

Municipal solid waste (MSW) disposal is facing increasing challenges from ever more stringent environmental restrictions imposed by government legislation and public concern. Most solid wastes go to landfill. However, existing landfills are rapidly being filled due to the growing volume of waste and because of the decreasing number of landfill sites and the difficulties in obtaining approval for new landfill sites. Alternatives to landfill are needed. Globally, incineration is becoming an increasingly used and important alternative technology for treating solid wastes, with the advantages of decreasing solid waste volume by up to 90% and of providing heat to make electricity or steam. The solid residues of incineration include bottom ash and flyash (the solids

---

\*To whom correspondence should be addressed.

captured from the gaseous emissions). An important unresolved problem with incineration is the safe disposal of its flyash, which is enriched in heavy metals during the combustion process and which is regarded as a hazardous material based on the legislation in many developed countries. The leaching of the heavy metals from the flyash by water in landfill environments has received considerable attention and has been addressed in the literature [1–5]. A pretreatment to detoxify the MSW flyash is necessary to clean the ash so that it can be subsequently used in construction or road industries. Many approaches could be used to achieve this purpose, including stabilization through thermal vitrification, solidification by adding solidifying agents to the ash to prevent hazardous metals from leaching out [6], and leaching pretreatment to remove the heavy metals from the ash and, possibly, allow recovery of the metal values from the leachate [7, 8]. From an economical and environmental perspective, the leaching pretreatment with metal recovery appears attractive.

A process named 3R for removing the heavy metals from MSW flyash was developed by Vehlow et al. [7] and was successfully operated at a pilot scale. The flue-gas washing water from the incinerator was acidic and was used to leach the flyash at a pH of about 1–3. After the treatment, the solid residue was reported to pass environmental regulations.

A laboratory pilot-scale process to treat flyash was developed by Legiec et al. [8]. The MSW incinerator ash was leached in NaCl + HCl solution at pH 3. Subsequently, the leachate was directly subjected to an electrowinning process to recover lead. Another potential flyash detoxification approach with the recovery of Pb, Cd and Zn in HCl solution was reported by McKinley et al. [9]. MSW flyash was treated in a HCl solution resulting in the rapid dissolution of Pb, Cd and Zn. A solid/liquid ratio of 1:200 was used in their leaching experiments. The leached Pb and Cd could be subsequently recovered by cementation with zinc dust.

The main purposes for studying leaching tests for flyash can be classified as: (1) assessment and guidance for the landfill disposal of flyash, (2) detoxification of flyash for subsequent use or disposal, (3) recovery of valuable metals from flyash, (4) and research into the structure and the formation mechanisms of flyash from incineration. There are few reports available in the literature on the systematic study of the leaching of MSW flyash over extended leaching conditions. The work in this paper presents the general leaching experimental results, as one of a series of reports to be published, in order to understand the leaching behaviour of MSW flyash over a wide range of experimental conditions and to shed some light on the structure of flyash and its formation mechanism.

## 2. Experimental

Two sources of MSW flyash from electrostatic precipitators were used in the present study, reported as flyash #1 and flyash #2. Flyash #1 was a fine

TABLE 1

Flyash composition (mg/g)

Element	Flyash #1	Flyash #2
Al	89.4	66.7
Ca	109.0	77.0
Cd	0.154	0.106
Co	0.028	0.009
Cr	0.514	0.494
Cu	1.030	0.420
Fe	19.2	18.7
K	24.7	47.0
Mg	15.6	15.8
Mn	2.200	0.830
Mo	0.050	0.020
Na	47.4	27.5
Ni	0.203	0.052
P	6.31	7.62
Pb	4.20	2.80
Ti	20.4	12.8
V	0.055	0.044
Zn	9.920	3.820
Sb	0.718	0.276
SiO <sub>2</sub>	357.0	363.0
Cl	28.8	45.0
S	22.1	7.3
CO <sub>2</sub>	15.0	32.0
As	0.104	0.102
Br	0.401	0.228

greyish powder and was used as received, while flyash #2 was a blackish powder having chunks of unburnt material and was sieved with an 80 mesh standard sieve before use. The elemental composition of both materials is listed in Table 1.

The leaching experiments were carried out in a flat-bottom flask with a magnetic bar to stir the slurry during leaching. The standard solid sample weight used was 10 grams and the lixiviant volume was chosen to set the desired solid-to-liquid ratio. The sampling of the leachate was regularly taken by syringe during leaching. About 7 to 10 ml slurry was drawn into a syringe and was then pushed through a 0.7  $\mu$ m filter unit, resulting in 6 ml clean leachate which was stored for later ICP analysis. The solid residue in the filter unit was returned to the reactor by reversing the same amount of fresh lixiviant through the filter in order to keep the slurry volume in the reactor constant.

The leachate samples were diluted by 10 times with 5% HNO<sub>3</sub> + 5% HCl solution and analyzed by induction coupled plasma (ICP) spectroscopy in a commercial laboratory. The chemical composition of solid samples from the

TABLE 2

Mass balance for flyash #2 leached in 2 M HCl, S/L=1:50, 2 h reaction time

Element	Content (mg/g ash)			Mass balance B*
	Flyash #2	Leachate	Residue	
Al	66.7	23.2	36.2	0.89
Ca	77	85.7	5.9	1.19
Fe	18.7	8.5	10.3	1.01
K	47	37.4	8.4	0.97
Mg	15.8	12.1	3.7	1.00
Mn	0.8	0.7	0.2	1.13
Na	27.5	16.3	7.7	0.87
Pb	2.8	2.7	0.4	1.11
SiO <sub>2</sub>	363	51.1	313.1	1.00
Zn	3.8	4.6	0.7	1.39
S	7.3	9.1	0.6	1.33

\* Mass balance B is defined as a ratio of total concentration in leachate and residue to the concentration in original ash.

original ash and the leached residue were analyzed using solid fusion followed by total digestion, then by ICP spectroscopy or atomic absorption spectroscopy (AAS) in another independent laboratory. The leachate results were consistent with the solid results, which was evident by the fact that the leachability changed smoothly and reasonably with changes in experimental conditions and that the mass balance analysis showed good agreement for most major elements, as shown in Table 2, where the mass balance ratio is, in most cases, close to unity. Therefore, the leachability in this work was calculated based only on the leachate composition, with a correction for mass loss during the sampling operation.

Chemicals were reagent grade, and deionized 18 M $\Omega$  (DI) water was used for all operations. Solution blanks were analyzed and used to correct for any background values. Standards were run for all major elements. Sample spiking for matrix correction was not carried out.

Scanning electron microscopy equipped with an energy dispersive absorption X-ray analyzer (SEM/EDAX) was used to characterize the flyash and leached residue. The particle samples were spread on a glued tape and gold coated under vacuum. In preparing samples for cross-section microscopy, the particles were mounted with epoxy resin and polished with diamond paste using propanol. Water was avoided because of concern that the chloride salts in the flyash samples might dissolve during sample preparation. An X-ray diffractometer was used to identify the phases in the flyash and flyash residues. An angle scanning rate of 2°/min over a range of 5 to 75° was used in the X-ray analysis.

Ontario Regulation 347 provides a standard test procedure (MOE LEP test) to determine whether a solid waste is hazardous. A slightly modified MOE LEP test procedure was used in the present work to evaluate the environmental impact of flyash before and after leaching treatment. Three grams of solid sample was mixed with 50 ml DI water in a 100 ml glass beaker which was stirred by a magnetic bar at room temperature. After 15 min of leaching, the pH in the slurry was measured by a pH meter. If the pH was greater than  $5.0 \pm 0.2$ , then 0.5 N HAc solution was added to adjust the pH down to 5.0; if the pH was less than 5.0, no HAc was added. At the leaching times of 1, 3, 6 and 22 hours, respectively, the pH was checked and adjusted with HAc solution to ensure the slurry pH was not above 5.0. The slurry volume was increased by DI water to 60 ml total after 22 hours of leaching. After two more hours of leaching, the slurry was filtered through a 0.7  $\mu\text{m}$  unit filter and the filtrate was sampled and stored in a 20%  $\text{HNO}_3$  and 20% HCl solution unit just before the ICP analysis.

### 3. Results and discussion

#### 3.1. Characterization of MSW flyash before and after leaching

The compositions of MSW flyash varies substantially, depending on the incineration technology, flue-gas treatment and operating conditions, as well as with the MSW feed stream composition. However, the main elements which compose flyash are the same; silicon, aluminum, calcium, magnesium, iron, potassium, sodium, chlorine, and sulphur. The speciation analysis by X-ray diffraction (XRD) of both flyashes is shown in Table 1. The XRD-detectable compounds for flyash #2 are predominantly  $\alpha$ -quartz and to a minor or trace degree CaO, NaCl, KCl,  $\text{CaSO}_4$  and an aluminosilicate compound, possibly  $\text{NaAlSi}_3\text{O}_8$ . For flyash #1, NaCl has a strong peak in the XRD spectrum, while the other compounds include  $\alpha$ -quartz, CaO, KCl,  $\text{CaSO}_4$  and an aluminosilicate compound.

It is commonly believed that, during the incineration of MSW, oxides of silicon, aluminum, iron and other metals form the core of the flyash particles and then volatile species such as lead and cadmium chlorides condense on the surface [10–12]. The core materials are mainly from the original source matrix and have undergone complete or incomplete oxidation, with an accompanying phase change at high temperature. Since the MSW stream varies greatly, the matrix of the flyash particles varies substantially, giving a wide diversity in size, particle structure and composition. The diversity in grain structure can be observed from Fig. 1, which shows the general microscopic features of the flyash used in this study. There are so many different shapes of particles that it is difficult to classify all of them. Some typical flyash particles include spheres and porous sinters apparently melted during incineration, agglomerations of many fine crystals and condensed flakes. Many of the fine crystals are attached to the surface of larger particles and some of these crystals remain even after HCl leaching, as shown in Fig. 2. The analysis carried out by EDAX indicates

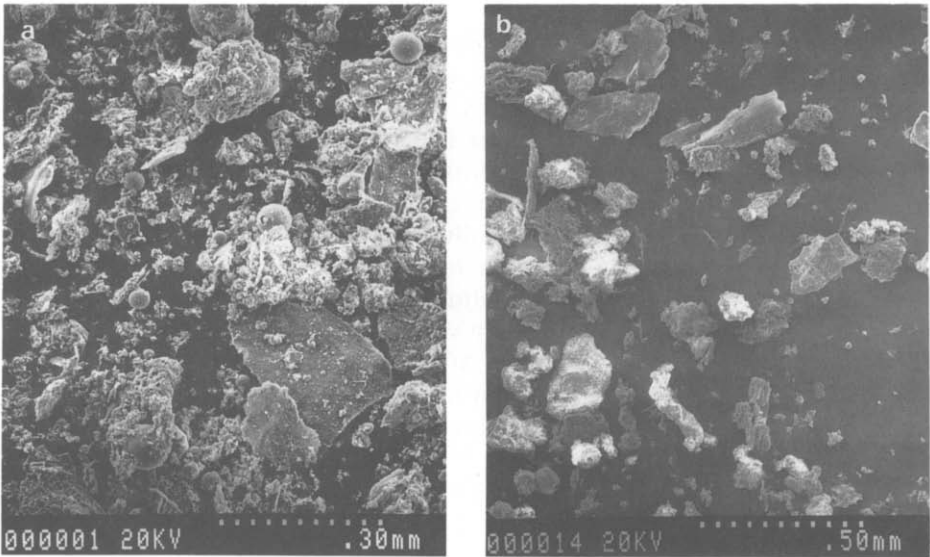


Fig. 1. Overview of flyashes, (a) flyash #1, and (b) flyash #2.

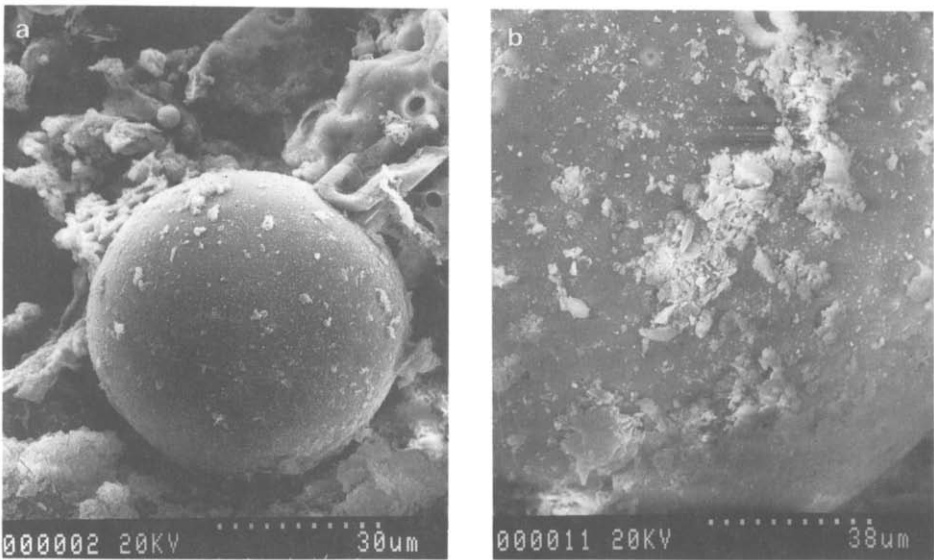


Fig. 2. SEM photograph of flyash #1 before (a) and after (b) HCl leaching, showing the surface crystals existing after HCl leaching at room temperature.

these fine crystals are, in most cases, oxides of silicon and aluminum, with traces of calcium, iron, and potassium. The diversity in the matrix constituents were even observed in the analysis of the cross-sections of leached residue samples, where silica or two or three of the elements (Si, Al, Ca, Fe, and even Ti) comprised the matrix of the particle. Occasionally, these were found with Na, K, S and Mg as well. The large variation of the waste feed causes this diversity in the matrix compositions.

Chloride compounds in the flyash are critical in the disposal of flyash because of their rapid leachability. In the analysis of polished cross-sections of flyash samples, some of common chloride phases were identified and are shown in Fig. 3, in which NaCl, KCl and CaCl<sub>2</sub> are present as single phases. The presence of these phases on the polished cross-section surfaces confirms the suitability of the sample-polishing procedure which used propanol rather than water.

An issue concerning HCl leaching is the extent to which the solvent attacks the matrix of the particles. Although the weight loss after HCl leaching reached 45% for flyash #2 and 54% for flyash #1, the microscopic analysis did not show significant changes in the residual flyash particle morphology or shape. A perfect sphere composed mainly of silicon and calcium oxide is presented in Fig. 4(a) after HCl leaching, clearly showing that HCl leaching does not damage such matrices. However, occasionally, the matrix of some particles with different compositions may show some damage from the HCl leaching. As an example, Fig. 4(b) shows a damaged sphere made up of needle-like grains which was analyzed and found to be titanium dioxide. Another species, originally completing the spherical structure, appears to have dissolved during the HCl leach. A similar case with iron oxide is shown in Fig. 4(c). Figure 4(d) is a portion of a sphere with an incomplete cover layer made of silicon and potassium, and also appears to have been attacked by the HCl lixiviant. The XRD-detectable phases in the HCl-leached residue were predominantly  $\alpha$ -quartz with minor amounts of hematite and trace amounts of an aluminosilicate phase (NaAlSi<sub>3</sub>O<sub>8</sub>) and CaSO<sub>4</sub>. The hematite phase is more prominent after leaching, indicating that hematite is not readily leached out under the experimental conditions (see Table 3 in Sect. 3.3). NaCl, KCl and CaO could not be detected in the HCl-leached residue, indicating that these compounds substantially dissolved.

### 3.2. Lixiviant comparison

Before the HCl medium was chosen as the lixiviant for the leaching of MSW flyash, some experiments were carried out using different solvents in order to compare their leaching efficiency. The leaching of flyash #1 was conducted in acid (HCl), alkali (NaOH) and water. The leachability of Cd, Pb, Zn and K is presented in Fig. 5. Clearly, the HCl acid medium achieved a better leachability for these elements. The leachability of cadmium in H<sub>2</sub>O and 2 N NaOH solution is much lower than that in HCl acid. The metals resembling Cd leachability behaviour include; Fe, Ca, Mg, Mn, Ti and Cr. These metals are

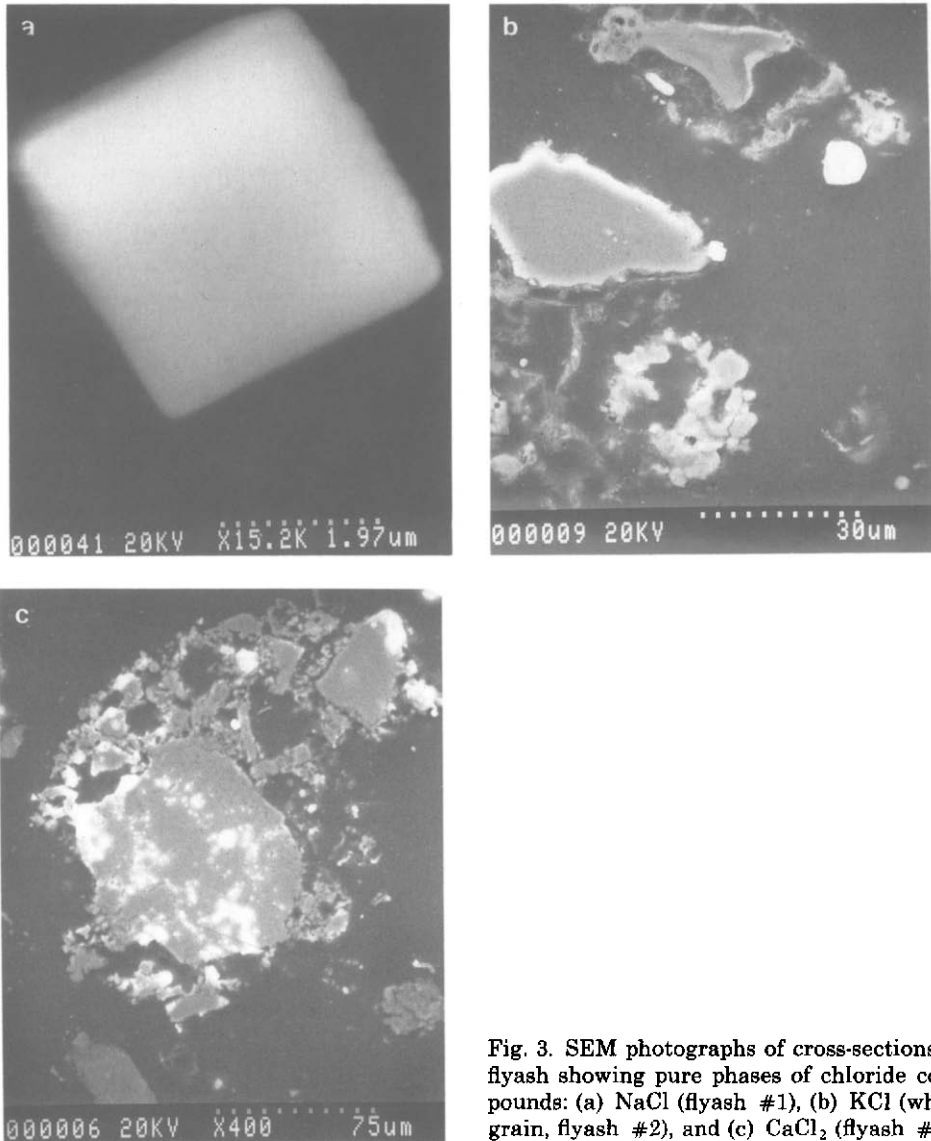
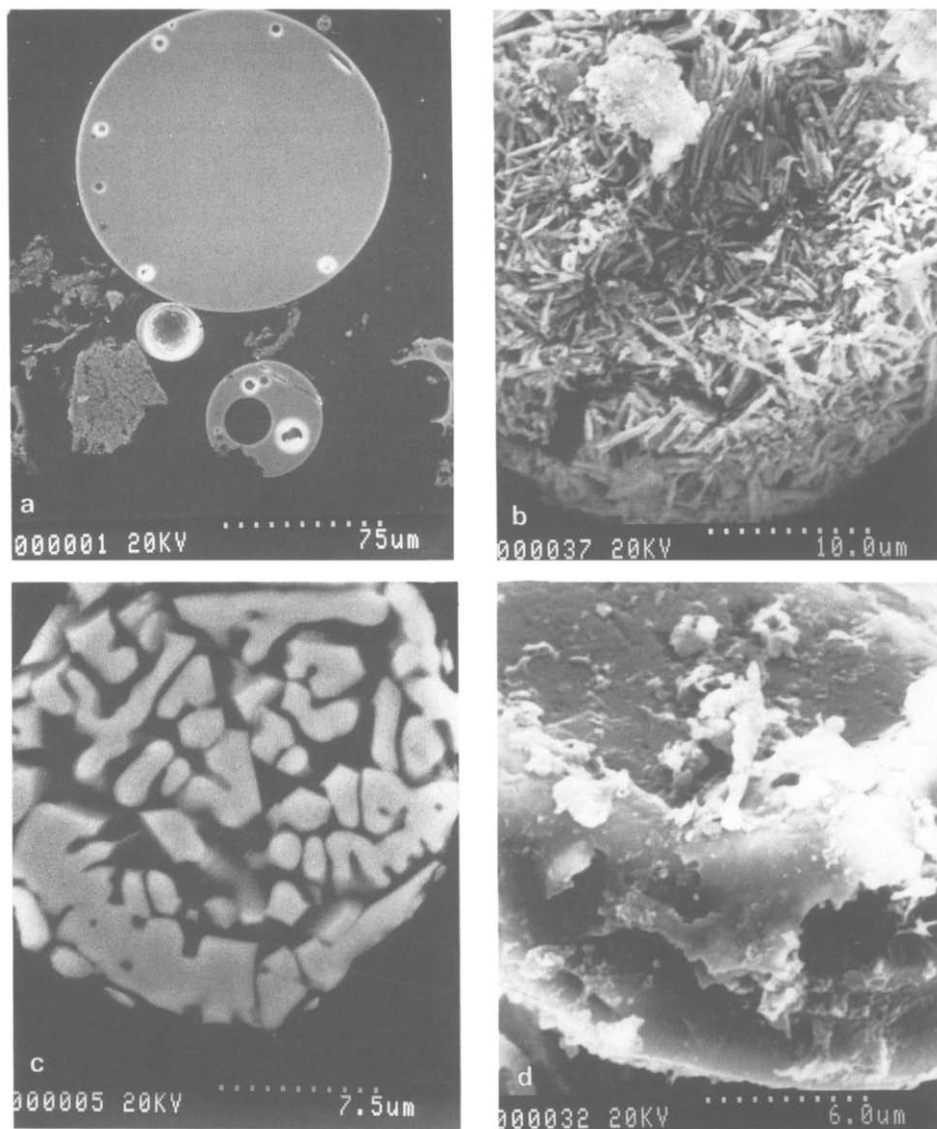


Fig. 3. SEM photographs of cross-sections of flyash showing pure phases of chloride compounds: (a) NaCl (flyash #1), (b) KCl (white grain, flyash #2), and (c) CaCl<sub>2</sub> (flyash #1).

virtually insoluble in water and 2 N NaOH solution. Lead and zinc, as shown in Fig. 5, represent another group of metals (amphoteric metals) which are slightly more soluble in 2 N NaOH than in water, although the leachability in NaOH is still less than in HCl solution. Aluminium and arsenic also belong to this group. Potassium, sodium and sulphur are highly leachable even in water. The slight differences in leachability for these latter elements in different media is attributed to the fact that compounds containing these elements may





**Fig. 4.** SEM photographs of leached residues showing: (a) a cross-section of a calcium silicate sphere unattacked by acid, (b) TiO<sub>2</sub> needle grains with a phase possibly leached out by acid, (c) a cross-section of iron phases with the empty space created by acid attack, and (d) a partially covered sphere after HCl leaching.

be partially combined with other phases which may not be readily dissolvable in water or alkaline media.

The above experiments showed the importance of solvent acidity in achieving a good leachability for most elements. In order to compare the effects of

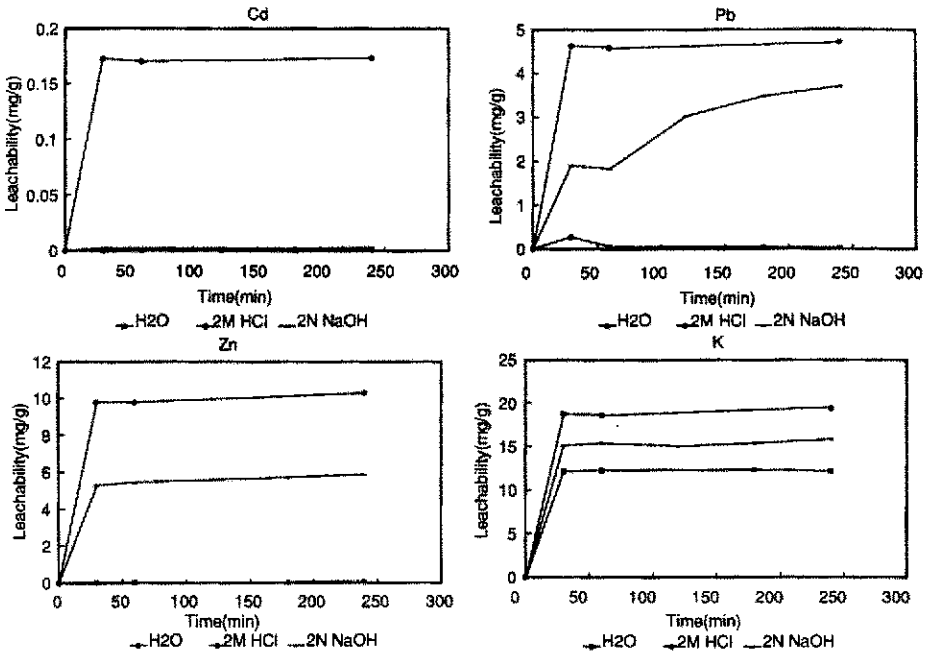


Fig. 5. Metal leachability of flyash #1 in various media vs. leaching time, S/L=1:50, and stirring.

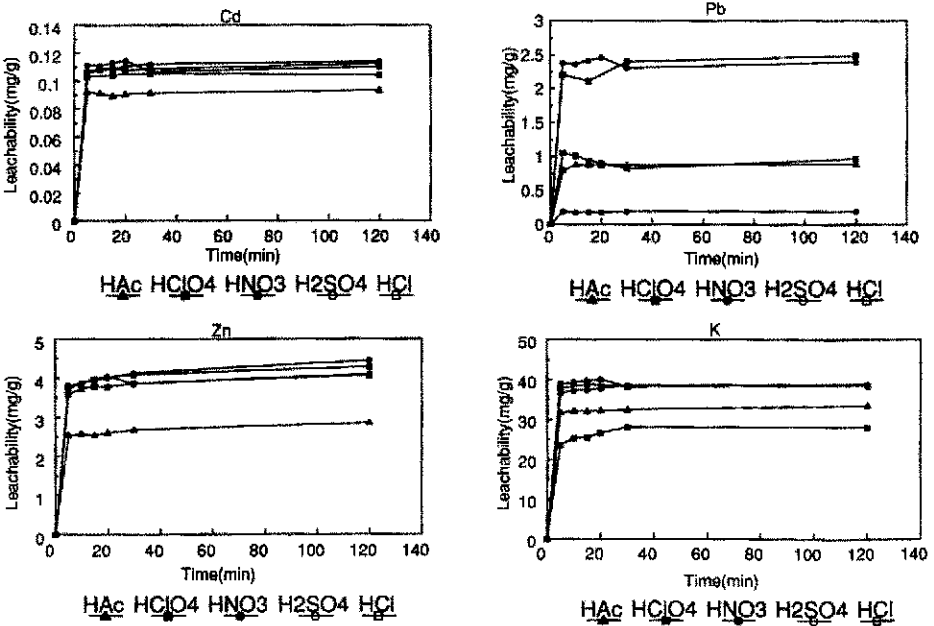


Fig. 6. Metal leachability of flyash #2 in various acids vs. leaching time, S/L=1:20, and stirring.

other chemical properties of the acids on the leachability of metals from flyashes, several acids were tested at the same normality for the leaching of flyash #2. The acids used in order of Lowry–Brønsted strength were; 2 M HClO<sub>4</sub>, 2 M HCl, 2 M HNO<sub>3</sub>, 1 M H<sub>2</sub>SO<sub>4</sub> and 2 M HAc. Figure 6 shows the leachability of Cd, Pb, Zn and K in these acids as a function of leaching time. HAc, having the lowest pK<sub>a</sub>, was the weakest lixiviant of the acids tested and the leachability of most elements in HAc medium are less than that in other acids. The other acids had almost the same leaching ability for most elements, such as Cd, Zn, Na, Al, Mn and S as shown in Fig. 6, and there was no correlation with acid strength.

The complexity of the leaching behaviour can be seen from the dissolution of lead. While the solubility of lead is expected to be low in sulphuric acid [9] due to the small solubility product, K<sub>sp</sub>, of lead sulphate, the leachability of lead in HClO<sub>4</sub> and HAc accounts for only half the amount found in HCl and HNO<sub>3</sub>. Possibly, HAc was too weak to attack some of the matrix phases containing lead, since HAc can form very soluble complexes with lead. HClO<sub>4</sub> is a strong oxidizing agent and could oxidize bivalent lead to PbO<sub>2</sub> which would be much less soluble in acid. The high lead leachability found using HNO<sub>3</sub>, an oxidizing acid, may be because the concentration used was 2 M, less than the 2.5 M which is reported to be the minimum concentration required for HNO<sub>3</sub> to oxidize Pb<sup>2+</sup> to PbO<sub>2</sub> and reduce the lead leachability [13].

The leachability of potassium in HClO<sub>4</sub> solution is even lower than that in HAc medium. The solubility of KClO<sub>4</sub> is about 20 g/l at 25 °C [14] which cannot account for the low extraction since potassium is unsaturated at about 1.3 g/l. Thus the acid choice depends as much upon the ability of the acid to attack the matrix as upon its acidity.

For lead, cadmium and zinc as well as almost all other elements, HCl was among the group of solvents to achieve the highest leachability, suggesting that HCl is the most efficient solvent for the detoxification of flyash and should provide the best extraction of the environmentally important metals.

### 3.3. HCl leaching

In order to relate the leachability of metals with the HCl concentration in the solution, a series of HCl concentrations of 0 to 6 M were tested on the leaching of flyash #2 at a solid/liquid ratio of 1:20 and room temperature. The plots of leachability of metals against HCl concentration are given in Fig. 7. Under the given leaching conditions, HCl concentration plays a significant role only in the lower concentration range. The corresponding leachability does not change significantly above about 0.5 M HCl for most elements, or above 1 M for lead and copper. For iron, the leachability increases with increasing HCl concentration for the whole concentration range tested, due to the slow attack and dissolution of hematite in concentrated HCl solutions [15] (see Fig. 4c).

The percentage of metals leached in 2 M HCl solution at a solid-to-liquid ratio of 1:20 is summarized in Table 3, where nearly complete leaching was achieved for the elements Cd, Pb, Zn and S.

TABLE 3

Metal leachability of flyashes in 2 M HCl solution, S/L=1:20, reaction time 2 h

Element	Flyash #1			Flyash #2		
	Ash content (mg/g)	Leachability		Ash content (mg/g)	Leachability	
		(mg/g)	(%)		(mg/g)	(%)
Al	89.4	37.02	41	66.7	22.94	34
Ca	109.0	106.35	98	77.0	79.16	103
Fe	19.2	7.64	40	18.7	7.77	42
K	24.7	18.20	74	47.0	38.55	82
Mg	15.6	10.18	65	15.8	11.99	76
Cd	0.15	0.16	102	0.11	0.10	99
Na	47.4	33.62	71	27.5	16.44	60
Pb	4.20	4.06	97	2.80	2.48	89
Si	166.0	44.65	27	169.6	4.51	3
Zn	9.92	9.08	91	3.82	4.29	112
S	22.1	17.45	79	7.32	9.26	127
Cr	0.51	0.06	12	0.49	0.04	8
Cu	1.03	0.58	56	0.42	0.23	56

A decrease of silica in the leachate with increase of HCl concentration, as seen in Fig. 7, is associated with the rapid formation of silica gel formed in concentrated HCl solutions. This effect causes a serious problem for the development of a leaching process. Under high HCl concentrations and large solid-to-liquid ratio conditions, the filtration of the slurry residue becomes very slow, and even impossible, due to the formation of a highly viscous gel. In contrast, coal flyash from a power plant, being leached in the same conditions, has good filtration characteristics, indicating that surface silica from MSW flyash is more active than that from coal flyash. The dissolved silica is unstable in acidic solution and quickly polymerizes to form silica gel. The rate of silica gel formation increases with increasing HCl and salt concentrations [16] and accounts for the filtration problem of high acid leachate. Controlling the pH between 1 and 3 can reduce the solubility of silica and retard the gel formation [16], but the silica accumulation with the recycling of leachate will certainly bring the problem back, if an industrialized process is developed for the leaching operation.

A detailed kinetic study of flyash leaching will be reported in future work.

### 3.4. Titration of flyash with HCl

Flyash is alkaline in water because of its content of alkaline and alkaline earth metal oxides and carbonates. Titration experiments can show the alkalinity of the flyash and the HCl consumption required to acidify the flyash slurry. A buffering effect by flyash with titration has been reported before [12].

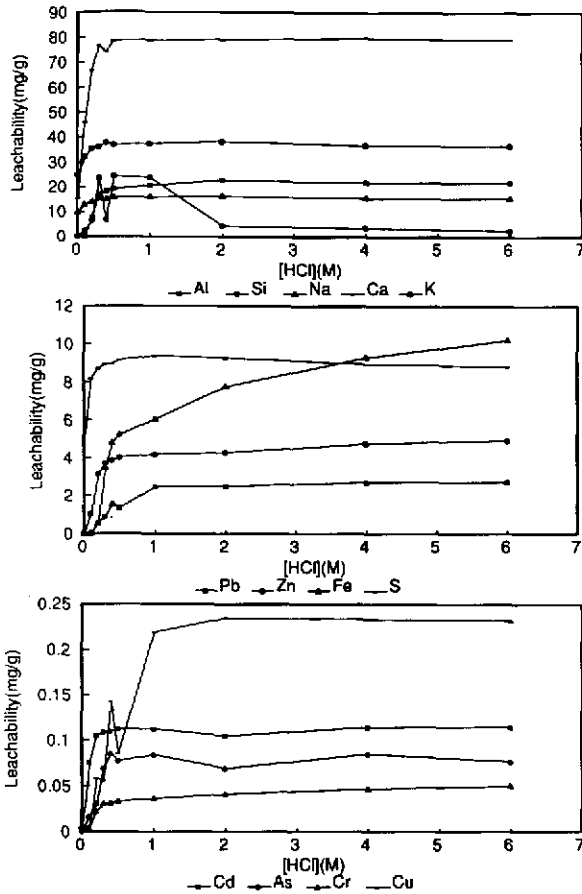


Fig. 7. Metal leachability of flyash #2 vs. HCl concentration, S/L=1:20, 2 h residence time and stirring.

The titration curves of the flyashes used in the present study are presented in Fig. 8. A 2 M HCl solution was used for titration and the time interval between the titrant addition measurements was 1 hour, which is long enough to ensure the system stabilized. Flyash #1, obviously, has a buffering capacity at a pH of about 4, while flyash #2 shows a smaller but similar effect. More HCl is required to reach pH 2 for flyash #1 than that for flyash #2, probably because flyash #1 contains more metal oxides. Water washed flyashes were subjected to titration experiments, and the results also are shown in Fig. 8. Both washed residues still show a buffering capacity at a pH of about 3.5. Almost the same amount of HCl is needed for the washed ash to reach a pH of about 3 as the original flyash. The titration for the water leachate and a standard NaOH solution, also given in Fig. 8, shows that the acid required to acidify these solutions is very small. The conclusion from these experiments is that a simple

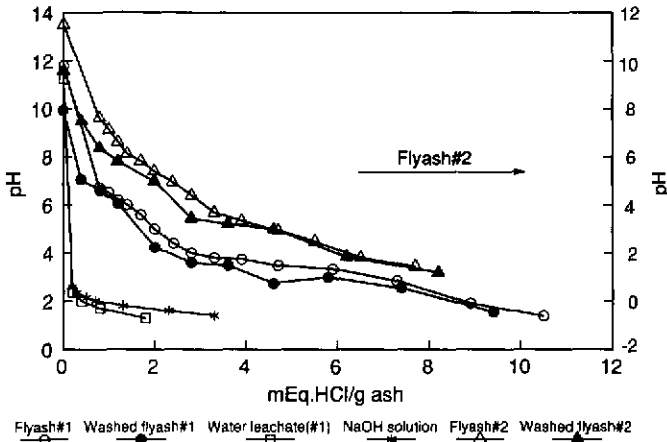


Fig. 8. Titration curves for flyash using 2 M HCl titrant. Mass of ash = 10 g, S/L = 1:20, and 1 h time between measurements. Water leachate is from the leaching of flyash #1 with water at S/L = 1:10 for 30 min. NaOH solution has an initial pH 11.5.

water wash pretreatment will not reduce the HCl consumption for the acid leaching operation.

### 3.5. Detoxification tests

Both original flyashes and their residues leached in HCl solution were subjected to the modified MOE LEP leach test described in the experimental section. The concentration of metals found from these tests are summarized in Table 4 and are compared with the regulatory limits set by Ontario Regulation 347. The leached residues have been treated with two types of leaching experiments: a regular leaching with 2 M HCl and S/L = 1:20 or a high solid-to-liquid ratio leaching at S/L = 1:5 with a HCl concentration of 1 M and 2 M. As can be seen, the cadmium and lead concentrations for flyash #1 and cadmium concentration for flyash #2 exceed the permitted level and both ashes, therefore, would be regarded as hazardous if they are subject to Reg. 347. However, after ashes were leached in HCl medium, the elements in MOE LEP test leachate were all below the hazardous concentrations, although Cd from the test with the high solid-to-liquid ratio leaching residue passed marginally.

## 4. Conclusions

Municipal solid waste flyash shows vast diversity in its composition and particle structure, unlike the generally similar particle shapes encountered with coal flyash. The comparison of NaOH, H<sub>2</sub>O, HCl, H<sub>2</sub>SO<sub>4</sub>, HNO<sub>3</sub>, HClO<sub>4</sub> and HAc solvents showed HCl to be most efficient lixiviant for removal of

TABLE 4

MOE LEP test for MSW flyashes (mg/l)

	Leaching conditions	Final leaching pH	Element				
			Cd	Pb	Zn	Cr	As
Flyash #1							
Untreated ash			5.62	10.43	193.20	0.15	0.00
Leached residue	2 M HCl, 2 h, S/L=1:20		0.00	0.00	1.74	0.08	0.00
	1 M HCl, 0.5 h, S/L=1:5	3.1	0.21	0.79	2.44	0.15	0.03
	0.5 M HCl, 0.5 h, S/L=1:5	4.2	0.24	0.89	7.26	0.09	0.00
Flyash #2							
Untreated ash			2.43	0.96	35.17	0.14	0.42
Leached residue	2 M HCl, 2 h, S/L=1:20		0.01	0.06	1.06	0.08	0.05
	1 M HCl, 0.5 h, S/L=1:5	2.85	0.07	0.34	1.03	0.07	0.03
	0.5 M HCl, 0.5 h, S/L=1:5	4.62	0.06	0.33	2.80	0.08	0.55
MOE limits			0.5	5.0	-	5.0	6.0

heavy metals from flyash. Since the flyash is very heterogeneous, many different matrix phases are present and the effectiveness of the acid extraction appears to depend on the chemical attack of the matrices. The bulk phases such as silica and calcium silicate are inert to HCl attack, while some particles with "exsolved" phases containing iron and titanium oxides appear to be more likely to be attacked HCl leaching.

The HCl concentration effect on the leachability depends on the elemental chemical activity and the particle structure. Most elements are not susceptible to additional leachability at concentrations above 0.5 M. Lead and copper dissolution increases with HCl acid strength up to 1 M. In contrast, iron dissolution was found to increase with increasing HCl concentration over the concentration range studied (0-6 M), and this behaviour is associated with the dissolution of hematite in the flyash particles in concentrated HCl solution.

An unresolved problem with concentrated HCl leaching of MSW flyash is the formation of silica gel, which is enhanced at high HCl concentrations and causes poor filtration. Control of pH or using dilute HCl concentrations may be used to reduce the solubility of silica and retard the formation of silica gel to ease the filtration problem, but it is believed that this problem will persist due to the accumulation of silica in the leachate, if leachate recycling is practised in an industrial setting.

The buffering effect of flyash in titration curves is attributed to the consumption of acid by solid compounds, not to water-soluble alkali metals. Therefore, the use of a water wash in an industrial operation cannot be used to reduce alkalinity of the flyash or its HCl consumption.

The flyashes used in this study would be deemed hazardous by the Ontario Reg. 347 (MOE LEP test). The residues leached in 2 M HCl at a S/L 1:20 are well below the environmental criterion in MOE LEP test and the residues leached at S/L 1:5 in 2 M HCl can pass the MOE LEP test marginally.

## References

- 1 S. Cernuschi, M. Giugliano and I. de Paoli, Leaching of residues from MSW incineration, *Waste Manage. Res.*, 8 (1990) 419–427.
- 2 S.E. Sawell, T.W. Constable and R. Klicius, Evaluation of contaminant leachability from residues collected at a refuse-derived fuel municipal waste combustion facility, *Environmental Canada*, IP-96, 1989.
- 3 C.W. Francis and G.H. White, Leaching of toxic metals from incinerator ashes, *J. Water Pollut. Control Fed.*, 59 (1987) 979–986.
- 4 H.A. Van der Sloot, G.J. De Groot, J. Wijkstra and P. Leenders, Leaching characteristics of incinerator residues and potential for modification of leaching, In: *Proc. Int. Conf. on Municipal Waste Combustion*, April 11–14, 1989, Hollywood, FL, Vol. 1, 2B-1–2B-19.
- 5 J.V. DiPietro, M.R. Collins, M. Guay and T.T. Eighmy, Evaluation of pH and oxidation–reduction potential on leachability of municipal solid waste incinerator residues, In: *Int. Conf. on Municipal Waste Combustion*, April 11–14, Hollywood, FL, Vol. 1, 2B-21–2B-43.
- 6 S.E. Sawell, R.J. Caldwell and T.W. Constable, Evaluation of solidified flyash from municipal waste incinerators, In: *11th Can. Waste Manage. Conf.*, Sept. 27–29, 1989, Montreal, Que. pp. 151–169.
- 7 J. Vehlow, H. Braun, K. Horch, A. Merz, J. Schneider, L. Stieglitz and H. Vogg, Semi-technical demonstration of 3R process, *Waste Manage. Res.*, 8 (1990) 461–472.
- 8 I.A. Legiec, C.A. Hayes and D.S. Kosson, Laboratory pilot scale evaluation of lead recovery from municipal solid waste incinerator ash, In: *Int. Conf. on Municipal Waste Combustion*, April 11–14, 1989, Hollywood, FL, Vol. 1, 4B-1–4B-9.
- 9 M.D. McKinley, G.W. Warren, S.M. Lahoti and K. Sreenivasarao, Stabilization and hydrometallurgical treatment of flyash from a municipal incinerator, *J. Hazardous Mater.*, 29 (1992) 255–273.
- 10 R.R. Greenberg, W.H. Zoller and G.E. Gordor, Composition and size distributions of particles released in refuse incineration, *Environ. Sci. Technol.*, 12 (1978) 566–573.
- 11 J.W. Graydon and D.W. Kirk, Characterization of flyash from a municipal solid waste incinerator, In: *EPD Congress 1992*, TMS, 1992, pp. 327–350.
- 12 J.L. Ontiveros, Ph.D. thesis, Rutgers, the State University of New Jersey, New Brunswick, NJ, May 1988.
- 13 N. Hara, The dissolution mechanism of cadmium and lead in nitric acid, *India Health* 5 (1967) 60–64.
- 14 Kirk-Othmer *Encyclopedia of Chemical Technology*, 3rd edn., Vol. 5, Wiley, New York, 1979.
- 15 H. Majama, Y. Awakura and T. Mishima, The leaching of hematite in acid solution, *Metall. Trans.*, 16B (1985) 23–30.
- 16 R.K. Iler, *The Chemistry of Silica*, Wiley, New York, 1979.