Utilization of municipal solid waste incineration (MSWI) fly ash in blended cement
Part 1: Processing and characterization of MSWI fly ash

J.E. Aubert *, B. Husson, N. Sarramone

Laboratoire Matériaux et Durabilité des Constructions (L.M.D.C.), INSA-UPS, 135 avenue de Rangueil, 31077 Toulouse cedex 4, France

Abstract

This paper is the first of a series of two articles dealing with the processes applied to MSWI fly ash with a view to reusing it safely in cement-based materials. Part 1 presents two stabilization processes and Part 2 deals with the use of the two treated fly ashes (TFA) in mortars. Two types of binder were used: an Ordinary Portland Cement (OPC) containing more than 95% clinker (CEM I 52.5R) and a binary blend cement composed of 70% ground granulated blast furnace slag and 30% clinker (CEM III-B 42.5N).

In this first part, two stabilization processes are presented: the conventional process, called "A", based on the washing, phosphation and calcination of the ash, and a modified process, called "B", intended to eliminate metallic aluminum and sulfate contained in the ash. The physical, chemical and mineralogical characteristics of the two TFA were comparable. The main differences observed were those expected, i.e. TFA-B was free of metallic aluminum and sulfate. The mineralogical characterization of the two TFAs highlighted the presence of large amounts of a calcium aluminosilicate phase taking two forms, a crystalline form (gehlenite) and an amorphous form. Hydration studies on pastes containing mixed TFA and calcium hydroxide showed that this phase reacted with calcium hydroxide to form calcium aluminate hydrates. This formation of hydrates was accompanied by a hardening of the pastes. These results are very encouraging for the reuse of such TFA in cement-based materials because they can be considered as pozzolanic additions and could advantageously replace a part of the cement in cement-based materials. Finally, leaching tests were carried out to evaluate the environmental impact of the two TFAs. The elements which were less efficiently stabilized by process A were zinc, cadmium and antimony but, when the results of the leaching tests were compared with the thresholds of the European landfill directive, TFA-A could nevertheless be accepted at landfills for non-hazardous waste. The modifications of the process led to a significant reduction in the stabilization of chromium, selenium and antimony.
© 2006 Elsevier B.V. All rights reserved.

Keywords: Waste management; Municipal solid waste incineration; Fly ash; Stabilization process; Characterization

1. Introduction

Issues related to environmental conservation and preservation have taken on great importance in our society in recent years. The decision-makers in political, economic and social life are paying more attention to concerns related to the environment. Deep changes are taking place in our ways of living and of working. Among these changes, waste management has become one of the principal issues. The authorities seek to privilege the re-use of waste in an environmentally and economically sustainable way.

The management of municipal solid waste illustrates this policy perfectly. Since July 2002 [1], European landfills are not authorized to receive this waste to which no pretreatments have been applied and must be reserved for the storage of ultimate waste. Replacement solutions must therefore be found. Thermal treatment is a valid option for reducing the amount of waste to be landfilled and, in most cases, for recovering the energy content of the waste. A recent paper by members of a European working group called "Phoenix" deals with the practical problems, recent research findings and solutions related to the management of MSWI residues [2].

* Corresponding author. Tel.: +33 5 61 55 66 97; fax: +33 5 61 55 99 49.
E-mail address: aubert@insa-toulouse.fr (J.E. Aubert).

The thermal treatment of MSW produces waste in its turn:

- bottom ash (coarse non-combustible materials and unburned organic matter rich in metal scraps and relatively poor in heavy metals),
- fly ash (fine particulate matter removed in a preliminary filter before the process to neutralize gaseous effluents, as the incinerator is equipped for a double dust removal process),
- and air pollution control (APC) residues which contain the neutralizing agent (lime or sodium bicarbonate).

These residues are considered as ultimate waste and, after a solidification and stabilization process, must be stored in landfill.

The recycling of industrial waste in civil engineering applications has undergone considerable development over a very long time. Coal fly ash, blast furnace slag and silica fumes are examples of the success of this research. Similarly, the reuse of hazardous waste has been under study for many years through technological work (studies of the effect of the residue on the properties of construction materials) and research on the environmental impact of such practices [3].

The small amounts of dangerous substances contained in bottom ash allow its reuse as material for road construction after weathering. This has been the case in particular in France for more than 10 years [4].

Fly ash and APC residues are characterized by their high chloride content and significant amounts of heavy metals and toxic organic compounds (especially PCDDs and PCDFs). The reuse of these residues is therefore more difficult because of their environmental impact. Over the last 12 years, the research has been focused on the study of stabilization and solidification of these residues by cementitious, organic or vitreous matrices before their landfilling. The most common processes of stabilization/solidification are based on the use of hydraulic binders and numerous studies deal with this topic [5–7]. Mangialardi et al. have investigated the feasibility of a combined washing-immobilization process as a means of optimizing the disposal of MSWI fly ash in a cementitious matrix [8,9]. An on-site preliminary treatment of MSWI air pollution control residues based on the use of a ferrous sulfate ($FeSO_4$) was studied by Lundtrop et al. [10]. Guerrero et al. have investigated the effects of a hydrothermal treatment on MSWI fly ash [11]. They show that practically 100% of chloride and metallic aluminum from the fly ash can be dissolved. Mizutani et al. have compared different chemical agents used for the treatment of MSWI fly ash (treatment with chelating agent, phosphate treatment and ferrite treatment) [12]. The authors conclude that all the treated materials show good results for the Japanese leaching test compared with the behavior of untreated MSWI fly ash. Huang and Lo have studied the stabilization of lead contained in MSWI fly ash by colloidal aluminate oxide [13]. This chemical fixation agent shows good efficiency (94.8%) for reducing the leachability of Pb. Jianguo et al. have investigated heavy metal stabilization in MSWI fly ash using heavy metal chelating agents [14]. The authors conclude that the heavy metals in fly ash can be stabilized more effectively by using heavy metal chelating agents than by using chemical agents such as sodium sulfide and lime.

N'zihou and Sharrock have studied the effects of the combination of water extraction and calcium phosphate stabilization of MSWI fly ash on its environmental impact [15]. Soluble phosphates have also been used by Geysen et al. to immobilize lead and zinc in scrubber residues from MSW combustion [16]. The immobilization of these elements was compared to the immobilization of cement and the authors conclude that the process is efficient.

In the most recent years, several researchers have studied the possibility using fly ash and APC in cement-based materials. This research can be classed in three groups. Some researchers have investigated the possibility of using these residues as raw materials for the production of Portland cement clinker [17]. Others have studied the use of fly ash and APC as mineral additions to concrete in two different ways:

- fly ash (or APC) directly introduced into concrete without preliminary treatment [18,19],
- fly ash (or APC) treated before their use in concrete, the treatment being based on preliminary washing [20].

The aim of our work is the safe use of MSWI fly ash in cement-based materials. Before its use, the fly ash is stabilized by the REVASOL® process developed and patented by the Solvay Company in collaboration with the Université Libre de Bruxelles. This process will be precisely described in Part 2.1. A previous paper [21] has shown that, from the mechanical and durability points of view, the treated fly ash (TFA) incorporated in concrete behaves like ordinary sand. Moreover, leaching tests carried out on TFA-containing concrete confirm that the stabilization process makes it possible to obtain materials without major risks for the environment. Even so, in another paper, Aubert et al. [22] have shown that, like all waste coming from municipal solid waste incineration, the TFA contains metallic aluminum (Al^0) that can lead to swelling when it is introduced into cement-based materials. This expansion is due to the reaction between Al and water in presence of alkalis coming from the cement, which releases hydrogen during the setting of materials containing TFA. These problems have been observed by many authors in MSWI bottom ash [23–25] and MSWI fly ash [6,7,11,26]. Moreover, TFA contains a high proportion of sulfate, which could be a problem for its use in cement-based materials. In fact, most of the materials used in concrete (binders, aggregate, water, etc.) have to be free of sulfate to prevent any problem of delayed ettringite formation that could lead to damage by expansion. The elimination of metallic aluminum and sulfate during the process applied to the MSWI fly ash could be profitable to its use in cement-based materials. It is one of the topics of this study.

This paper is the first of two articles. These two articles deal with the processes applied to MSWI fly ash with a view to using it safely in cement-based materials. In the present paper, two processes of stabilization will be presented: the conventional process and a process modified to eliminate metallic aluminum and sulfate. The physical, chemical and mineralogical characteristics of the two treated fly ashes will be given and the effects of the modifications made to the conventional process on the char-

acteristics of TFA analyzed. The results include the leachability of harmful elements, measured according to the standardized European leaching test (EN 12457-1). Finally, the reactivity of these ashes in presence of calcium hydroxide will be analyzed as an introduction to the second paper in the series. Part 2 deals with the use of the two TFA in mortars, considering two types of binder: an Ordinary Portland Cement (OPC) containing more than 95% clinker (CEM I 52.5R) and a binary blend cement composed of 70% ground granulated blast furnace slag and 30% clinker (CEM III-B 42.5N).

2. Experiments

2.1. Materials and stabilization processes

The ash studied, coming from a single French incinerator, was chosen among 10 fly ashes from European incinerators because it was very rich in sulfates and heavy metals. It represented the most difficult case for the evaluation of the efficacy of the stabilization process. This process can be divided into three successive steps [27]:

- Water dissolution of ash: the washing of fly ash has a double objective. First, it removes the soluble salts (especially chlorides) contained in the ash, so as to improve its behavior in cement-based materials (especially the kinetics of setting). Secondly, it allows the sodium contained in halite (NaCl) to be recovered for use in technical soda plants.
- Phosphation with phosphoric acid to stabilize heavy metals.
- Calcination to eliminate organic compounds (especially PCDDs and PCDFs), at a temperature higher than 600 °C.

Derie [27] has studied the effects of this process on the stabilization of harmful elements. His results show that the process is able to stabilize heavy metals contained in MSWI fly ash with the exception of chromium, arsenic and antimony. A recent study by Piantone et al. using a micro-characterization approach confirms these results, especially the high level of fixation of Pb and Zn resulting from the process [28].

Two variations on the stabilization process presented above were applied to the same sample of selected fly ash. In the conventional process, called "A", the ash was treated in a pilot unit of 25 kg/h capacity. The water/fly ash ratio for the washing step was 10 and the step lasted about one hour. Although the water/fly ash ratio was high, sulfates were only very slightly dissolved. The phosphoric acid/fly ash ratio was 15%. The calcination was carried out in a rotary kiln at a temperature of 750 °C.

The variation on this conventional process, called process "B", was developed in the laboratory. The washing step of the treatment was modified in order to eliminate metallic aluminum and calcium sulfate. Sodium carbonate (Na_2CO_3) was added to the washing water for two reasons:

- this addition increases the pH value during washing, which enables metallic aluminum to be dissolved,

- Na_2CO_3 reacts with $CaSO_4$ to form Na_2SO_4, which is very soluble, and calcite $CaCO_3$, which is inert in cement-based products.

The other steps and parameters of the process were the same as those used in the conventional treatment.

2.2. Chemical, physical and mineralogical characterization procedures

Major oxides composition was estimated on the basis of the macroelemental analysis carried on digested samples by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) and the minor elements by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). The water content (drying at 100 °C) and the loss on ignition (calcination at 1000 °C) were also measured. The metallic aluminum content was determined with a method measuring the amount of hydrogen gas produced by the oxidation reaction of metallic aluminum [22]. The calcite ($CaCO_3$) content was determined from the CO_2 volume measured during acidic dissolution.

The size distribution of TFA was analyzed by means of a laser particle size analyzer using a dry suspension with an air pressure varying from 0 to 4 bars.

The crystalline phases were identified using a Siemens D5000 powder X-ray diffractometer equipped with a monochromator using a Kα (λ = 1789 Å) cobalt anticathode. A scanning electron microscope was used to study the morphology of the particles of TFA.

2.3. Leaching behavior

The TFA were characterized for heavy metal leachability according to the European standard EN 12457-1 extraction test: 100 g (dry weight) of TFA samples were extracted using distilled water at an L/S ratio of 10 for 24 h. The eluates were filtered using a 0.45 μm membrane filter. Various tests were done on the leachates: measurement of the pH, of the Soluble Fraction (SF), of sulfate content and minor elements content by ICP-MS.

2.4. Reactivity in presence of calcium hydroxide

Mineral additions used in hydraulic binders may be categorized as inert, pozzolanic materials or latent hydraulic cements. The pozzolanic reaction is a reaction of the pozzolanic material with water and CaO. It produces hydrates and leads to the hardening of the mixture. The calcium hydroxide $Ca(OH)_2$ could be introduced into the mixtures but it generally comes directly from the hydration of Ordinary Portland Cement.

To study the potential pozzolanic activity of the two ashes, two pastes were prepared by mixing 75% of TFA and 25% of calcium hydroxide ($Ca(OH)_2$). The hydration products were identified using an X-ray diffractometer. The pastes were cured in polyethylene tubes at 20 °C. At several hydration times, a piece of paste was manually sawn with a hacksaw to prevent increase of temperature. Then the sample was crushed, dried

Table 1
Chemical composition of ashes

Major oxides content (%)			Minor elements content (mg/kg)				
Oxides	TFA-A	TFA-B		TFA-A	TFA-B		TFA-A	TFA-B
CaO	25.2	30.0	Zn	24046	25250	Mo	49	<40
SiO_2	20.7	21.1	Pb	8816	8396	Bi	30	35
P_2O_5	13.6	12.5	Sn	2883	3132	Ce	30	31
SO_3	11.6	0.4	Cr	2078	778	Ga	21	22
Al_2O_3	10.0	10.2	Ni	1889	<500	La	15	14
MgO	2.7	3.0	Cu	1714	1837	Nd	11	<10
Fe_2O_3	2.7	1.5	Ba	1521	1059	Nb	11	<10
TiO_2	1.7	2.0	Sb	1457	2149			
Na_2O	1.4	1.8	Cd	586	609			
K_2O	1.4	1.2	Sr	399	<400			
MnO	0.2	0.1	W	227	192			
Free chlorides	0.0	0.1	Zr	149	132			
Water content	0.2	0.8	As	120	102			
Ignition loss	6.5	8.7	Co	79	44			

with acetone (at a temperature of 40 °C for a few minutes) and manually ground to <40 μm.

3. Results and discussion

3.1. Effects of process type on chemical and physical characteristics

The elemental compositions of the ashes are presented in Table 1. The chemical compositions of the two ashes are comparable. They contain large amounts of calcium, silicon, phosphorus (due to the stabilization process) and aluminum. The washing step of both processes dissolved the chlorides contained in the ash. The addition of Na_2CO_3 in process-B was efficient: TFA-B is free of sulfates as expected. The minor elements content of the two ashes is comparable. Large amounts of heavy metals can be seen, especially zinc, lead, chromium and cadmium.

Table 2 indicates the proportions of calcite and metallic aluminum in each TFA. TFA-B contained a large amount of calcite due to the reaction between calcium sulfate and sodium carbonate. Moreover, the increase of pH value during the washing step enabled metallic aluminum to be dissolved. The amount of residual aluminum in TFA-B was below the measurement threshold of our method (<0.07%).

These results show that the modifications made to the process gave the desired results: TFA-B was free of metallic aluminum and sulfate.

The physical characteristics of TFA are presented in Table 3. The modifications in the stabilization process significantly increased the surface area of the TFA. The values in the comparison of bulk density and specific gravity confirm this result.

Table 2
Calcite ($CaCO_3$) and metallic aluminum contents

	TFA-A	TFA-B
Calcite (%)	1	17
Metallic aluminum (%)	0.13–0.35	<0.07

Table 3
Physical characteristics of the ashes

	TFA-A	TFA-B
Bulk density (g/cm^3)	2.81	2.71
Specific gravity (g/cm^3)	2.95	2.86
BET surface area (m^2/g)	2.26	18.6

The TFA-B particles were more porous than TFA-A. Moreover TFA-B contained particles of neo-formed calcite, which were small. This could also explain the increase in surface area. The porosity of the particles can be observed on the SEM micrograph (Fig. 1) and is characteristic of the calcium phosphate phase. The size distribution of TFA confirms this characteristic. In fact, the increase of air pressure (0–4 bars) destroys large porous particles to form smaller particles as shown in Fig. 2. The porosity of the TFA, especially TFA-B, could lead to problems of workability of cement-based materials. The water used in these materials would be absorbed by the TFA, thus leading to a serious worsening in the workability characteristics, which could be compensated for by using a plasticizer or by adding water.
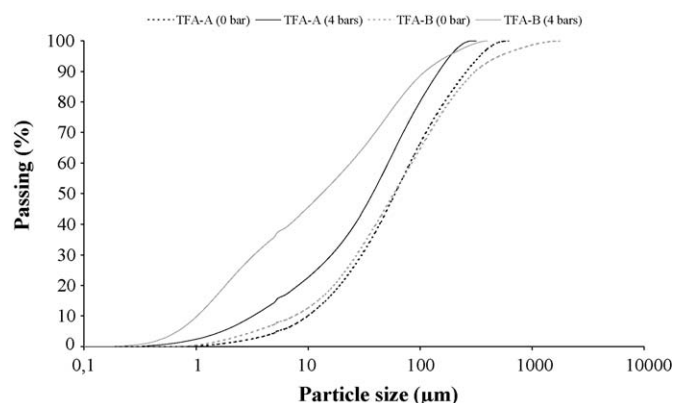

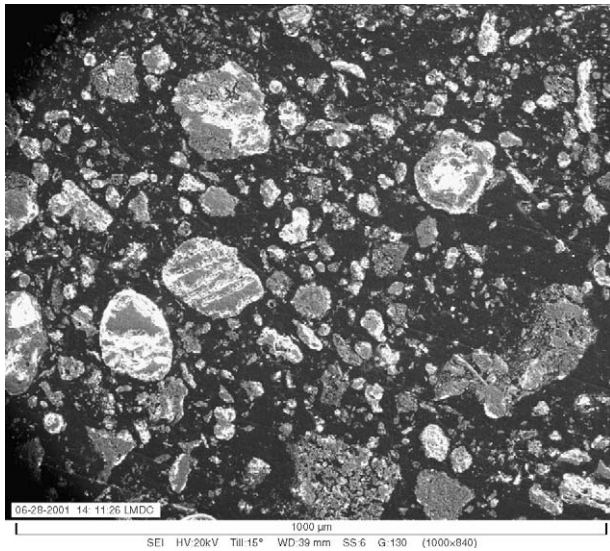Fig. 1. Variation of size distribution of ashes with air pressure.

Fig. 2. Scanning electron micrograph of TFA-A.

3.2. Effects of process type on mineralogical composition

The XRD patterns of the two TFA are presented Figs. 3 and 4. The minerals contained in TFA-A were, in order of decreasing content: minerals of the gehlenite group ($Ca_2Al_2SiO_7$), calcium phosphates including apatite ($Ca_5(PO_4)_5(OH,F,Cl)$) and whitlockite (β-$Ca_3(PO_4)_2$), anhydrite ($CaSO_4$), quartz (SiO_2), titanium oxides including titanite ($CaTiSiO_5$) and perovskite ($CaTiO_3$), and hematite (Fe_2O_3). These minerals were accompanied by an amorphous phase (identified by the presence of a halo on the XRD pattern). Another technique was used to better characterize this amorphous phase (scanning electron microscope with an energy dispersion spectrometer and electronic microprobe). The results, not presented in this paper, show that this amorphous phase was a calcium aluminosilicate phase. This part of the mineralogical characterization will be published in another article.

The main difference in the mineralogical composition of the two TFA concerned the disappearance of anhydrite ($CaSO_4$) in TFA-B, which was replaced by calcite ($CaCO_3$) as a direct consequence of the modification of the washing step.

The phosphation step of the process was efficient and apatite group minerals were formed. These minerals are considered to be very geochemically stable mineral phases and to be able to trap toxic metals [12,15–16,27–29].

The minerals contained in the two ashes can be considered as inert except for the anhydrite (only in TFA-A) and the calcium aluminosilicate phase which occurred in two forms: a crystalline form (gehlenite) and an amorphous form. Studies using an electronic microprobe have shown that these two forms have the same chemical composition but one is crystallized and the other not [30]. This is a consequence of the cooling rate of the MSWI fly ash and the same observations have been made by Delville et al. in a study of the mineralogical composition of MSWI bottom ash [31]. The reactivity of these minerals contained in the two TFA will be studied in Part 3.4.

3.3. Leaching behavior

The results of the leaching tests are given in Table 4. These results are the average of three tests on different samples. The concentrations of the solutions were expressed per dry mass of solid (mg/kg).

The results of the leaching tests carried out on TFA-A confirm those obtained by Derie [27]. The process did not efficiently stabilize chromium, and its efficiency was poor for antimony and cadmium. The reasons why these elements were weakly stabilized remain incompletely understood and some complementary studies would be useful. In the case of chromium, the calcination during the process led to the oxidation of some Cr(III) to Cr(VI) which is the soluble form of chromium. This could explain why the release of chromium was so high. Some experiments are in progress to try to reduce the chromium during the calcination step of the process.
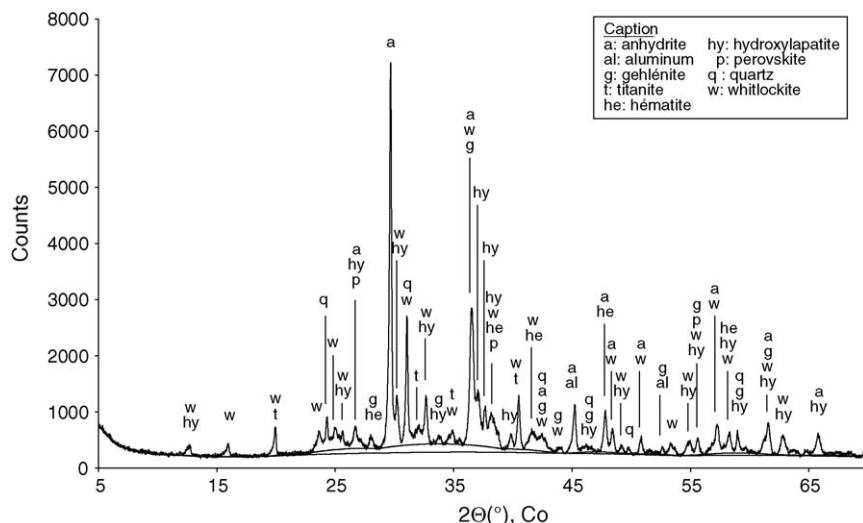

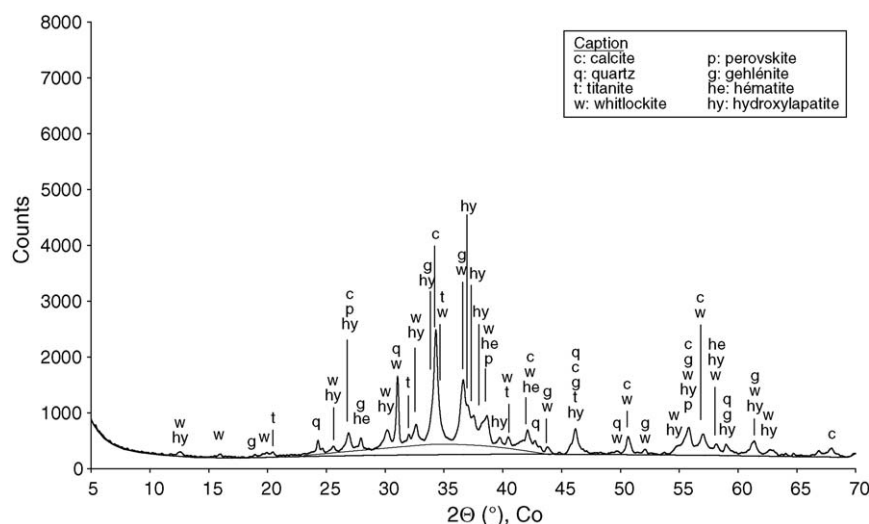Fig. 3. XRD pattern of TFA-A.

Fig. 4. XRD pattern of TFA-B.

As was the case during the washing step of the treatment, the solubility of sulfate was very low (about 0.8 g/l). This is apparently not a problem of kinetics because the leaching tests were carried out over 24 h. The low solubility of anhydrite is one of the reasons for the addition of Na_2CO_3 in process B.

If we compare the behavior of the two ashes to leaching, the main differences concern the release of chromium, selenium and antimony (higher for TFA-B) and the release of zinc, nickel and cadmium (higher for TFA-A). Na_2CO_3 is often used to extract the chromium (with or without NaOH) [32]. So, the addition of Na_2CO_3 during the washing step of process B could transform the insoluble chromium in a soluble form, which could explain the high mobility of chromium in TFA-B.

Finally, the results of the leaching tests can be compared with the thresholds of the European Landfill directive to evaluate the environmental impact of the two TFAs. In fact, no thresholds exist concerning a scenario of reuse and the thresholds of the

Table 4
Concentrations of leached elements

Elements	Concentrations of leached elements		European landfill directive		
	TFA-A	TFA-B	Inert	Non-hazardous	Hazardous
As (mg/kg)	0.169	0.032	0.5	2	25
Ba (mg/kg)	1.741	0.113	20	100	300
Cd (mg/kg)	0.203	0.003	0.04	1	5
Cr (mg/kg)	1.112	33.384	0.5	10	70
Cu (mg/kg)	0.012	0.007	2	50	100
Mo (mg/kg)	0.269	0.200	0.5	10	30
Ni (mg/kg)	0.553	<0.0001	0.4	10	40
Pb (mg/kg)	0.004	0.008	0.5	10	50
Sb (mg/kg)	0.091	2.390	0.06	0.7	5
Se (mg/kg)	0.098	0.670	0.1	0.5	7
Zn (mg/kg)	7.628	0.057	4	50	200
P (mg/kg)	9.837	<0.100	–	–	–
SF (g/kg)	11.0	5.4	4	60	100
SO$_4$ (g/kg)	7.578	0.826	1	20	50
pH	6.600	10.3	–	>6	–

landfill directive are the only ones currently available. TFA-A would have to be sent to landfills for non-hazardous waste because of the significant release of zinc, cadmium and antimony, which are above the limit values for waste acceptable at landfills for inert waste. The values of nickel and selenium are slightly higher than those recommended by the directive. TFA-B would have to be disposed of in landfills for hazardous waste because of its significant release of chromium, selenium and antimony.

3.4. Reactivity in presence of lime

The XRD patterns of the lime pastes mixed into TFA-A and TFA-B are presented in Figs. 5 and 6 respectively. The pastes tested were 2, 14 and 28 days old. The pattern of anhydrous mixtures is also presented. In both cases, we observe a significant consumption of calcium hydroxide and the formation of calcium aluminate hydrates. In the case of TFA-A, the consumption of calcium hydroxide is accompanied by a strong consumption of anhydrite ($CaSO_4$). No gypsum is detected. So the consumption of anhydrite is not due to its hydration but to its reaction with calcium hydroxide. These two minerals form ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$) as can be observed on the patterns. The amount of ettringite formed progressively increases over time. The formation of ettringite needs a source of aluminum. By considering the mineralogical composition of TFA, we can conclude that the calcium aluminosilicate phase, which occurs in two forms, a crystalline form (gehlenite) and an amorphous form, must be reactive in presence of calcium hydroxide. It can be observed on the patterns even though the main peak of gehlenite overlaps the main peak of whitlockite and a secondary peak of anhydrite.

These conclusions are confirmed by the study of the reactivity of TFA-B in presence of calcium hydroxide. In this case, the consumption of calcium hydroxide is slightly lower than in the case of TFA-A. The hydration of the paste leads to the formation of a carboaluminate phase ($Ca_8Al_4O_{14}CO_2 \cdot 24H_2O$) due to the absence of the calcium sulfate. Once again the calcium
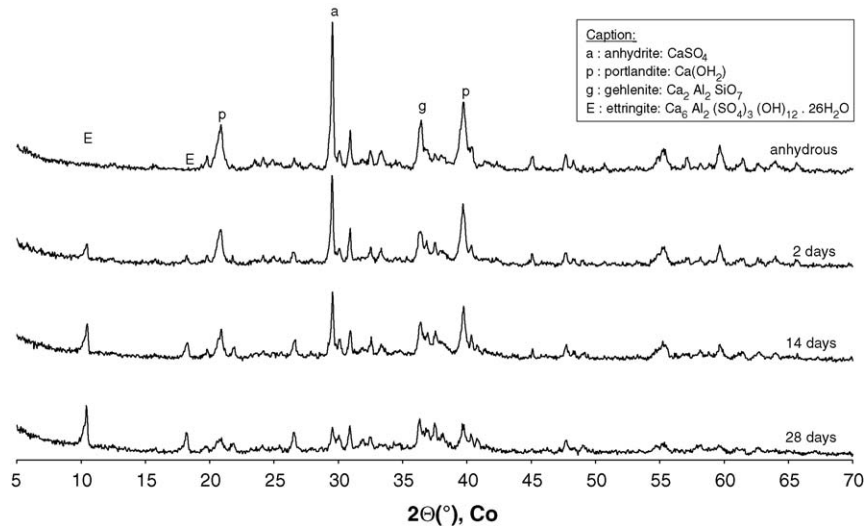
Fig. 5. XRD patterns of pastes containing 75% of TFA-A and 25% of calcium hydroxide.
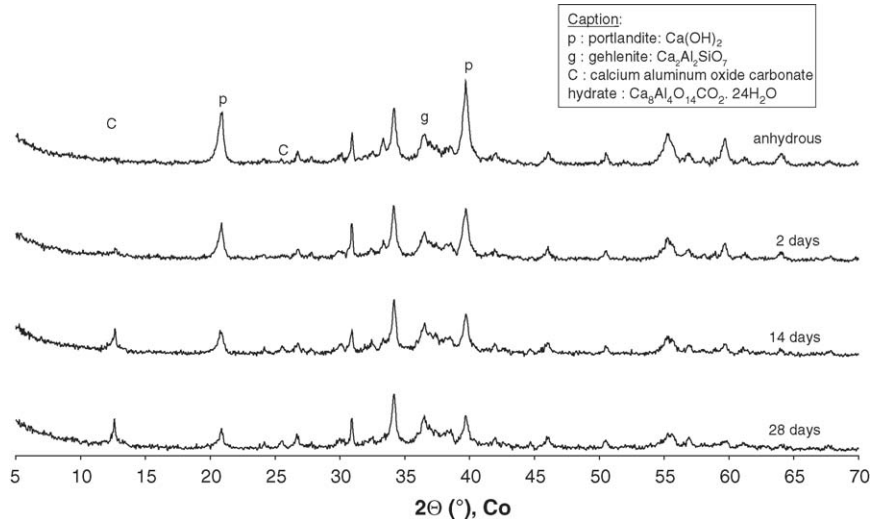

Fig. 6. XRD patterns of pastes containing 75% of TFA-B and 25% of calcium hydroxide.

aluminosilicate phase necessarily reacts in the presence of calcium hydroxide. In both cases, the hydration of the pastes leads to the hardening of these pastes. This hardening begins to be noteworthy after about 1 week of hydration.

These reactions and the activities of both ashes with calcium hydroxide are very interesting in connection with the possible reuse of these wastes in cement-based materials. In fact, TFA can be considered as pozzolanic additions and could advantageously replace a part of the cement in cement-based materials.

4. Conclusion

This paper is the first of two articles. In this part, two processes of stabilization have been presented: the conventional process based on the washing, phosphation and calcination of the ash and a process modified in order to eliminate the metallic aluminum and sulfate contained in the ash. The physical characterization of the two TFAs shows that these ashes can be considered as fine

additions. The size distributions of the two ashes are similar. The main difference concerns the porosity of the particles. Both ashes are porous but TFA-B is more porous than TFA-A. This porosity could lead to a loss of workability when the ashes are introduced into cement-based materials. These problems will be studied in Part 2 of this series. From a mineralogical and chemical point of view, both processes produce comparable ashes. The only differences observed are those expected, i.e. TFA-B is free of metallic aluminum and sulfate. The mineralogical characterization of the two TFAs highlights the widespread presence of a calcium aluminosilicate phase, occurring in two forms, a crystalline form (gehlenite) and an amorphous form. Hydration studies on pastes of mixed TFA and calcium hydroxide show that this phase reacts with calcium hydroxide to form calcium aluminate hydrates. This formation of hydrates is accompanied by a hardening of the pastes. These results are very encouraging in the perspective of reusing these TFAs in cement materials because they can be considered as pozzolanic additions and they could advantageously

replace a part of the cement in cement-based materials. The last point of this first part of the study concerns the behavior of the two TFAs to leaching. According to the comparison between the results of leaching tests and the European landfill directive, TFA-A could be accepted at landfills for non-hazardous waste. The modifications of the process lead to a significant reduction in the stabilization of chromium, selenium and antimony and TFA-B would have to be disposed of in landfills for hazardous waste. These results are worrying if this waste is to be reused in cement-based materials and it will be imperative to study the environmental impact of the TFA-containing mortars to ensure the ecological compatibility of these materials. The behavior of these TFAs in mortars will be studied from the mechanical and environmental points of view in Part 2 of these papers.

Acknowledgement

References

[1] Council directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities, 16/7/1999, L182/1-19.

[2] T. Sabbas, A. Polettini, R. Pomi, T. Astrup, O. Hjelmar, P. Mostbauer, G. Cappai, G. Magel, S. Salhofer, C. Speiser, S. Heuss-Assbichler, R. Klein, P. Lechner, Management of municipal solid waste incineration residues, Waste Manage. 23 (2003) 61–88.

[3] M. Cyr, J.-E. Aubert, B. Husson, P. Clastres, Recycling waste in cement-based materials: a studying methodology, in: Conference on the Use of Recycled Materials in Building and Structures - RILEM 2004, November 9–11, Barcelona, Spain, vol. 1, 2004, pp. 306–315.

[4] Ministère de l'environnement, direction de la prévention des pollutions et des risques, service de l'environnement industriel, 'Elimination des mâchefers des résidus urbains', Circular of 9 May 1994.

[5] P. Ubbriaco, D. Calabrese, Solidification and stabilization of cement paste containing fly ash from municipal solid waste, Thermochim. Acta 321 (1998) 142–150.

[6] E. Fernandez, A. Macias, A. Guerrero, M.P. Lorenzo, S. Goni, Influence of the cement type on the stabilisation of fly ashes from municipal solid waste incineration, in: G.R. Wooley, J.J.J.M. Goumans, P.J. Wainwrigth (Eds.), Waste Materials in Construction, Elsevier Science Ltd., 2000, pp. 169–177.

[7] S. Braymand-Morel, P. Clastres, A. Pellequer, Mineralogical, hydraulic and mechanical characterisation of solidified and stabilised MSWI fly ash. Contribution of blast furnace slag, in: G.R. Wooley, J.J.J.M. Goumans, P.J. Wainwrigth (Eds.), Waste Materials in Construction, Elsevier Science Ltd., 2000, pp. 260–266.

[8] T. Mangialardi, A.E. Paolini, A. Polettini, A. Sirini, Optimization of the solidification/stabilization process of MSW fly ash in cementitious matrices, J. Hazard. Mater. B70 (1999) 53–70.

[9] T. Mangialardi, Disposal of MSWI fly ash through a combined washing-immobilisation process, J. Hazard. Mater. B98 (2003) 225–240.

[10] K. Lundtorp, D.L. Jensen, M.A. Sørensen, H. Mosbæk, T.H. Christensen, On-site treatment and landfilling of MSWI air pollution control residues, J. Hazard. Mater. B97 (2003) 59–70.

[11] A. Guerrero, E. Fernandez, A. Macias, S. Goni, Hydrothermal treatment of fly ash from municipal solid waste incineration, in: G.R. Wooley, J.J.J.M. Goumans, P.J. Wainwrigth (Eds.), Waste Materials in Construction, Elsevier Science Ltd., 2000, pp. 178–185.

[12] S. Mizutani, H. Van der Sloot, S.-I. Sakai, Evaluation of treatment of gas cleaning residues from MSWI with chemical agent, Waste Manage. 20 (2000) 233–240.

[13] W.-J. Huang, J.-S. Lo, Synthesis and efficiency of new chemical fixation agent for stabilizing MSWI fly ash, J. Hazard. Mater. B112 (2004) 79–86.

[14] J. Jianguo, W. Jun, X. Xin, W. Wei, D. Zhou, Z. Yan, Heavy metal stabilization in municipal solid waste incineration fly ash using heavy metal chelating agents, J. Hazard. Mater. B113 (2004) 141–146.

[15] A. N'zihou, P. Sharrock, Calcium phosphate stabilization of fly ash with chloride extraction, Waste Manage. 22 (2002) 235–239.

[16] D. Geysen, K. Imbrechts, C. Vandecasteele, M. Jaspers, G. Wauters, Immobilization of lead and zinc in scrubber residues from MSW combustion using soluble phosphates, Waste Manage. 24 (2004) 471–481.

[17] P.-H. Shih, J.-E. Chang, L.-C. Chiang, Replacement of raw mix in cement production by municipal solid waste incineration ash, Cement Concrete Res. 33 (2003) 1831–1836.

[18] C. Collivignarelli, S. Sorlini, Reuse of municipal solid wastes incineration fly ashes in concrete mixtures, Waste Manage. 22 (2002) 909–912.

[19] L. Bertolini, M. Carsana, D. Cassago, A. Quadrio Curzio, M. Collepardi, MSWI ashes as mineral additions in concrete, Cement Concrete Res. 34 (2004) 1899–1906.

[20] E. Mulder, Pre-treatment of MSWI fly ash for useful application, Waste Manage. 16 (1–3) (1996) 181–184.

[21] J.-E. Aubert, B. Husson, A. Vaquier, Use of municipal solid waste incineration fly ash in concrete, Cement Concrete Res. 34 (2004) 957–963.

[22] J.-E. Aubert, B. Husson, A. Vaquier, Metallic aluminum in MSWI fly ash: quantification and influence on the properties of cement-based products, Waste Manage. 24 (2004) 589–596.

[23] J. Péra, L. Coutaz, J. Ambroise, M. Chabannet, Use of incinerator bottom ash in concrete, Cement Concrete Res. 27 (1997) 1–5.

[24] B. Quénée, G. Li, J.-M. Siwak, V. Basuyau, The use of MSWI (Municipal Solid Waste Incineration) bottom ash as aggregates in hydraulic concrete, in: G.R. Wooley, J.J.J.M. Goumans, P.J. Wainwrigth (Eds.), Waste Materials in Construction, Elsevier Science Ltd., 2000, pp. 422–437.

[25] G. Pecqueur, C. Crignon, B. Quénée, Behaviour of cement-treated MSWI bottom ash, Waste Manage. 21 (2001) 229–233.

[26] C. Chan, D. Kirk, H. Marsh, The behaviour of Al in MSW incinerator fly ash during thermal treatment, J. Hazard. Mater. B76 (2000) 103–111.

[27] R. Derie, A new way to stabilize fly ash from municipal incinerators, Waste Manage. 16 (1996) 711–716.

[28] P. Piantone, F. Bodénan, R. Derie, G. Depelsenaire, Monitoring the stabilization of municipal solid waste incineration fly ash by phosphation: mineralogical and balance approach, Waste Manage. 23 (2003) 225–243.

[29] B.S. Crannell, T. Taylor Eighmy, J.E. Krzanowski, J. Dykstra Eusden Jr., E.L. Shaw, C.A. Francise, Heavy metal stabilization in municipal solid waste combustion bottom ash using soluble phosphate, Waste Manage. 20 (2000) 135–148.

[30] J.-E. Aubert, Valorisation d'une cendre d'incinérateur d'ordures ménagères traitée par le procédé Revasol® dans des bétons hydrauliques, PhD thesis, Université Paul Sabatier, Toulouse, France, 2002.

[31] N. Delville, Phases reliques et phases de haute température: répartition des métaux lourds, in: Quel avenir pour les MIOM, Orléans (France), 2001, pp. 23–32.

[32] S.S. Potgieter, N. Panichev, J.H. Potgieter, S. Panicheva, Determination of hexavalent chromium in South African cements and cement-related materials with electrothermal atomic absorption spectrometry, Cement Concrete Res. 33 (2003) 1589–1593.