Utilization of municipal solid waste incineration (MSWI) fly ash in blended cement
Part 2. Mechanical strength of mortars and environmental impact

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Abstract

This second of two articles dealing with the utilization of MSWI fly ash in blended cement studies the effects of two variants of the stabilization process on the behavior of the treated fly ash (TFA) introduced into cement-based mortars. From a technological point of view, the modifications of the process are very efficient and eliminate the swelling produced by the introduction of MSWI fly ash in cement-based mortars. TFA has a significant activity in cement-based mortars and can also advantageously replace a part of the cement in cement-based material. From an environmental point of view, the results of traditional leaching tests on monolithic and crushed mortars highlight a poor stabilization of some harmful elements such as antimony and chromium. The use of a cement rich in ground granulated blast furnace slag (GGBFS) with a view to stabilizing the chromium is not efficient. Since neither adequate tests nor quality criteria exist to evaluate the pollutant potential of a waste with a view to reusing it, it is difficult to conclude on the environmental soundness of such a practice. Further experiments are necessary to investigate the environmental impact of TFA introduced in cement-based mortars depending on the reuse scenario.

1. Introduction

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 such research. Similarly, the reuse of hazardous waste has been under study for many years and interest in it is increasing worldwide for many reasons. First, if the waste has binding properties (hydraulic or pozzolanic), it allows a reduction in the use of Portland cement clinker. This leads to a reduction in the cost of the concrete and is indirectly beneficial for the environment because of the reduction of CO_2 emissions associated with the manufacture of Portland cement clinker. Second, it represents an interesting alternative to final landfill disposal and, again, the economic impact is significant. The main problem of such a practice is the environmental impact of the hazardous waste introduced into the cement-based materials.

This paper deals with the reuse of MSWI fly ash in cement-based materials. MSWI fly ash and air pollution control (APC) residues are characterized by the presence of heavy metals and toxic organic compounds (especially PCDDs and PCDFs), which make reuse more difficult because of the environmental impact.

In recent years, several researchers have studied the possibility of using fly ash and APC residues in cement-based materials. Mulder [1] studied the possibilities of removing a number of leachable elements from MSWI fly ash (by means of washing) before its useful application as a road base construction material. Collivignarelli and Sorlini [2] introduced MSWI fly ash (after a washing step) into concrete in addition to natural aggregates. The results show that similar behavior (compressive strength and environmental impact) was observed in concrete produced with natural aggregates and in waste-containing concrete. Bertolini et al. [3] replaced part of the Portland cement with MSWI fly and bottom ashes for concrete production. The

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authors conclude that these wastes show good pozzolanic behavior and so contribute to the development of the strength of the concrete. However, the oxidation of metallic aluminum contained in MSWI residues leads to the production of hydrogen in fresh concrete that could damage the concrete. The authors propose a treatment to prevent this problem (wet grinding of the residues).

These results as a whole show that the reuse of MSWI fly ash in cement-based materials could be interesting and confirm the findings presented in a previous paper [4].

Two variations of a stabilization process (the REVASOL® process developed and patented by the Solvay Company in collaboration with the Université Libre de Bruxelles) have been presented and studied in the first part of this series of two articles [5]. The conventional process (called "A") is based on the washing, phosphation and calcination of the fly ash. In the variant of the conventional process (called "B"), sodium carbonate Na_2CO_3 is added to the washing water in order to dissolve metallic aluminum and sulfates.

The characterization of the two treated fly ashes (TFAs) presented in the previous part of this work [5], shows that the only difference between these two ashes is the absence of metallic aluminum and sulfate in TFA-B. Moreover, hydration studies on pastes containing mixed TFA and calcium hydroxide showed that the TFAs have pozzolanic properties and could advantageously replace a part of the cement in cement-based materials. However, the leaching behavior of both TFAs is critical if utilization of the material in engineering applications is to be pursued. In fact, the leaching of chromium, selenium and antimony is significant, in particular for TFA-B. So, this pollution potential necessarily implies a study of the environmental impact of TFA-containing mortar. It is recognized, in particular with the experimental stabilization treatment by hydraulic binders, that cement-based materials are able to fix harmful elements contained in waste. Laforest and Duschesne have studied the effects of various binders on Cr ion fixation and they conclude that a sample containing only ground granulated blast furnace slag (GGBFS) is the most effective [6,7]. Rha et al. [8] have studied the stability of hardened slag paste for the stabilization/solidification of wastes containing heavy metal ions and in particular chromium. They have shown that the stabilization of chromium ions is mainly due to the substitution of calcium aluminate hydrates. For these reasons, two types of binder were used in this study: the first one was an ordinary Portland cement (OPC) containing more than 95% of cement clinker (CEMI 52.5R as specified in European standard NF EN 197-1 [9]) and a binary blend cement composed of 70% GGBFS and 30% cement clinker (CEMIII-B 42.5N) in the intention of stabilizing chromium.

The experimental work presented in this paper has two objectives. First, the effects of the two variants of the stabilization process on the characteristics of ash-containing mortars will be studied from the mechanical and environmental points of view. Second, the effects of the nature of the binder on the behavior of MSWI fly ashes in cement-based mortars will be analyzed.

2. Experimental work

2.1. Materials

The chemical compositions of the two cements are listed in Table 1. These were determined by atomic absorption spectrometry after fusion of the cement sample at 1100 °C with a mixture of tetraborate metaborate lithium followed by dissolving with concentrated HNO_3.

French standard siliceous sand was used to make the mortars. For each TFA, four compositions of mortars were studied: two reference mortars (100% CEMI and CEMIII) and two ash-containing mortars (75% cement and 25% TFA-A or TFA-B). The term "binder" will be used for the cement or for the cement and TFA mixtures. The sand/binder ratio was equal to 3 for all compositions. The water/binder ratios and the presence or absence of a plasticizer were determined according to the effects of TFA on the fluidity of fresh mortars.

2.2. Experimental procedures

The fluidity of fresh mortars was measured according to the French standard NF P 15-437 [10]. The method involves measuring the time taken by a cement mortar to flow from the large compartment of a workability measuring device and reach a fixed horizontal reference line cut into the wall of a second compartment, when subjected to vibration.

The swelling of fresh cement-based mortar was quantified using hydrostatic weighing to measure the variation of volume of an elastic, impermeable membrane containing the mortar under study [11]. The sample, immersed in a water bath, was hung on a balance connected to a computer which recorded the weight every 5 min with a precision of 0.1 g (the mass of the membrane containing the paste was approximately 200 g). The temperature in the water bath was controlled and equal to 20 °C.

The 4 cm × 4 cm × 16 cm mortar prisms were cast in steel molds, demolded after 1 day and then cured at 20 °C under water according to the standardized European EN 196-1 test method [12]. The samples used for leaching tests were stored at 20 °C in sealed bags.

Table 1
Chemical composition of CEMI 52.5R and CEMIII/B 42.5N (wt.%)

	SiO$_2$	CaO	MgO	Al$_2$O$_3$	Fe$_2$O$_3$	K$_2$O	Na$_2$O	SO$_3$	LOI
CEMI	20.3	62.8	2.5	4.5	2.3	0.7	0.2	3.1	1.9
CEMIII/B	30.9	46.7	5.7	8.9	1.2	0.2	0.5	2.5	1.8

LOI, loss on ignition.

Table 2
Effect of TFA on fluidity of fresh mortars

Mixture	Cement (g)		TFA (g)		Water/binder ratio	Flow time (s)
	CEMI	CEMIII	TFA-A	TFA-B		
1	450	–	–	–	0.50	10
2	337.5	–	112.5	–	0.50	21
3	337.5	–	–	112.5	0.50	>30
4	–	450	–	–	0.50	1
5	–	450	–	–	0.47	10
6	–	337.5	112.5	–	0.47	20
7	–	337.5	–	112.5	0.47	>30

At four hydration times (2, 7, 28 and 90 days), the prismatic specimens were initially broken into two pieces which were then tested for compressive strength according to the standardized European EN 196-1 test method.

The hydration reactions of the two binders in presence of TFA were studied on 28-day-old cement pastes. These pastes were prepared with the same binder compositions as those of the mortar presented above. They were cured in polyethylene tubes at 20 °C for 28 days. A piece of paste was manually sawn with a hacksaw to avoid increasing the temperature and then the sample was crushed, dried with acetone (at a temperature of 40 °C for a few minutes) and manually ground to <40 μm. The crystalline phases were identified by means of a Siemens D5000 powder X-ray diffractometer equipped with a monochromator using a Kα ($\lambda = 1.789$ Å) cobalt anticathode.

The environmental study was performed using two leaching tests carried out on 28-day-old mortars: one on crushed material according to the European standard EN 12457-2 [13] and the other on monolithic material according to the French standard NF P X 31-211 [14]. The test on monolithic material was carried out on 4 cm × 4 cm × 5 cm pieces, obtained from the sawing of the 4 cm × 4 cm × 16 cm prisms. The test on crushed material was carried out on a sample crushed to less than 4 mm. All the tests consisted of one extraction lasting 24 h at a 10:1 liquid to solid ratio, using distilled water. The eluates were filtered using a 0.45 μm membrane filter. The leachates were characterized for pH, soluble fraction (SF), and concentration of minor elements (which was measured by inductively coupled plasma-mass spectrometer, ICP-MS).

3. Results and discussion

3.1. Effects of TFA on the fluidity of fresh mortars

The fluidity of fresh mortars is given in Table 2. The water demand of CEMIII was lower than that of CEMI. As it was decided to keep the workability of the mixtures constant (instead of fixing the water content), the water content of the CEMIII-containing mortars was decreased. The substitution of TFA in place of cement led to a strong loss of workability, especially in the case of TFA-B. For the TFA-B-containing mortars, the flow time exceeded 30 s. This loss of workability of the TFA-containing mortars can be explained by the porosity of the ashes studied in part 1 of this series. Moreover, the significant increase of water demand in the case of TFA-B could

be explained by the formation of ultrafine neoformed calcite which would lead to a large BET surface area (18.6 m²/g for TFA-B versus 0.35 m²/g for the two cements used). The loss of workability could be compensated for by using a superplasticizer or by adding water. So, to keep a constant workability and constant water content, a superplasticizer was added to ash-containing mortars. That gave the compositions of each mixture studied in the rest of this article. These compositions are listed in Table 3.

3.2. Effects of TFA on the swelling of fresh mortars

The volume variations of the six compositions of mortar are presented in Fig. 1. For the two reference mortars (I-R and III-R), a slight shrinkage is observed over the first 24 h. But for the ash-containing mortars, the volume increase depends on the nature of the ash and binder. The greatest expansion is obtained with I-A. This expansion is due to the reaction between the metallic aluminum contained in TFA-A (0.13–0.35% [5]) and the water in presence of alkalis coming from the cement, which releases hydrogen in fresh mortar during its setting. In a previous paper [11], the evolution of hydrogen gas release during the setting of ash-containing cement paste was measured and XRD studies showed that the high sulfate content in the TFA-A ($SO_3 = 11.6\%$ [5]) did not play any role in this phenomenon because the ettringite formation occurred after the end of the expansion reactions. No swelling was observed when TFA-B was used with either CEMI or CEMIII, which confirms the results obtained during the characterization of
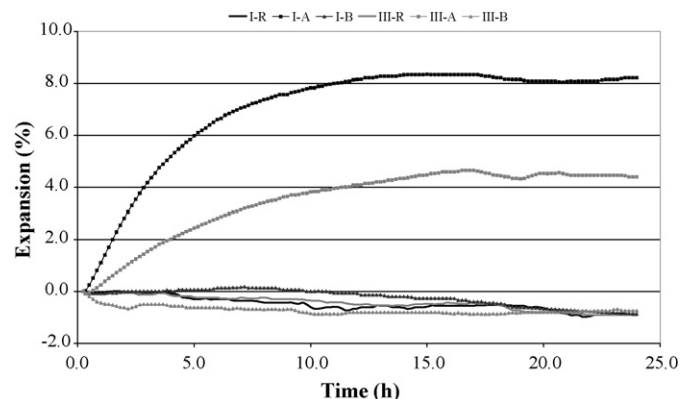

Fig. 1. Expansion of fresh mortars.

Table 3
Compositions of mortars

Composition	Cement (g)		TFA (g)		Water (g)	Superplasticizer (g)
	CEMI	CEMIII	TFA-A	TFA-B		
I-R	450	–	–	–	225	0
I-A	337.5	–	112.5	–	225	1.35
I-B	337.5	–	–	112.5	225	2.70
III-R	–	450	–	–	211.5	0
III-A	–	337.5	112.5	–	211.5	0.45
III-B	–	337.5	–	112.5	211.5	2.25

the two ashes: the variations of the process eliminate metallic aluminum and sulfate and, consequently, expansion of the ash-containing mortar is avoided. In the case of TFA-A, the expansion with CEMIII is less than that observed with CEMI. This result can be explained by the difference in composition of these two binders. CEMIII contains 70% GGBFS and 30% of cement clinker whereas CEMI only contains cement clinker. So, the alkalinity of CEMI is much higher than that of CEMIII, which leads to a greater dissolution into the pore solution of the metallic aluminum contained in MSWI fly ash and subsequent expansion.

3.3. Effects of TFA on mechanical strength of mortars

The development of the compressive strength of mortars between days 2 and 90 is given in Table 4. It can be seen that the smaller the quantity of cement, the lower the compressive strength. But the decrease of compressive strength caused by TFA strongly depends on (1) the nature of the ash and the binder and (2) the occurrence or not of swelling in the mortar. The compressive strength of the two references (I-R and III-R) is different, as is to be expected since the strength class of the two binders is different (52.5 MPa for CEMI and 42.5 MPa for CEMIII) as are the water/binder ratios. So, to allow comparisons to be made between the different mixtures, it is better to calculate the activity index (i.e. the compressive strength of standard mortar bars prepared with 75% test cement plus 25% addition by mass, expressed as a percentage of the compressive strength of standard mortar bars prepared with 100% test cement). The variation of the activity index of the four ash-containing mortars is presented in Fig. 2. To evaluate the activity of the two ashes, the experimental results were compared to two references values, the first of which is the activity index of an inert addition

computed using Bolomey's relation in its simplest form:

$$R_c = f_c k \left(\frac{C}{W} - 0.5 \right)$$

where R_c is the compressive strength of the mortars (MPa), f_c the standard strength of the cement (MPa), k a coefficient that depends on the aggregates, and C and W are the cement and water content (by mass), respectively.

If the cement type is considered to be the same for the two mixtures, the coefficients f_c and k are constant. It is then possible to calculate the theoretical activity of an inert addition, which corresponds to the reduction in the cement/water ratio of the mixture. The value of this index is 66.7% (noted "inert" in Fig. 2). The second reference activity value was calculated considering coal fly ash frequently used in concrete. According to European standard NF EN 450-1 [15], the activity index of standardized coal fly ash at 28 days and at 90 days must not be less than 75 and 85%, respectively. These values are referred as "coal fly ash" in Fig. 2.

The worst results for compressive strength were obtained with the TFA-A, which contains a significant amount of metallic aluminum. The study of the fresh TFA-A-containing mortars has shown a significant expansion of these mortars, which is less marked when CEMIII is used. The results for the compressive strength confirm these observations. Large cracks due to this expansion were observed in TFA-A-containing mortars and strongly decreased the compressive strength of the mortar. So, the activity index of TFA-A is below the value for an inert addition when CEMI is used and near this value when CEMIII is used. Although mixture III-A expands, the substitution of TFA-
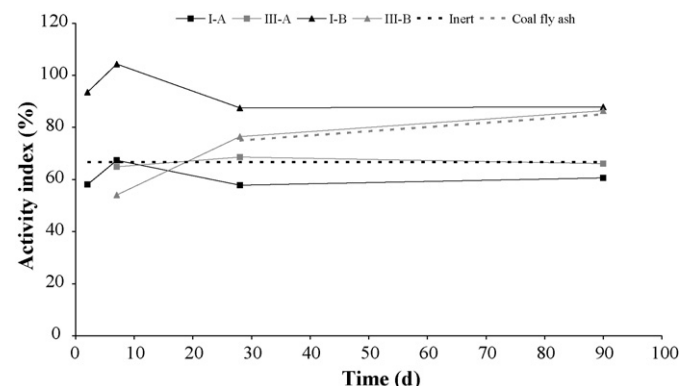
Table 4
Compressive strength of mortars

Composition	Compressive strength (MPa)			
	2	7	28	90
I-R	31	46	64	66
I-A	18	31	37	40
I-B	29	48	56	58
III-R	11	37	51	59
III-A	–	24	35	39
III-B	–	20	39	51

Fig. 2. Activity index of TFA introduced into CEMI and CEMIII mortars.

Caption:
A: anhydrite: $CaSO_4$ - P: portlandite: $Ca(OH)_2$ - E: ettringite: $Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$
C: calcium aluminum oxide carbonate hydrate: $Ca_8Al_4O_{14}CO_2.24H_2O$ - Ca: calcium aluminum oxide hydrates: $Ca_4Al_2O_7.xH_2O$ and $Ca_3Al_2O_6.xH_2O$
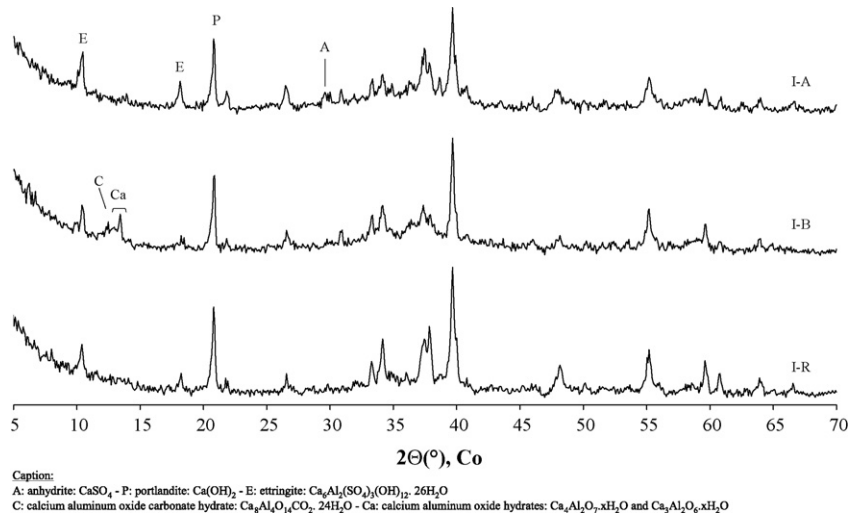
Fig. 3. XRD patterns of 28-day-old CEMI pastes.

A in place of CEMIII does not involve a loss of mechanical strength greater than that caused by the reduction in the quantity of cement. So, TFA-A has a non-negligible activity that compensates for the effect of the cracking of the mortar due to its swelling.

The results for the compressive strength of the TFA-B-containing mortars confirm the activity of TFAs. In fact, TFA-B is free of metallic aluminum and sulfate and no expansion is observed on mortar prepared with TFA-B. The activity indexes of TFA-B are nearly the same for the two binders and higher than that of coal fly ash at 28 and 90 days. Only the rate of increase of these indices is different depending on the binder used (slower for CEMIII).

This significant activity of TFA (better observed on TFA-B in the absence of swelling) can be explained by its pozzolanic effect, highlighted in part 1 of this series of articles [5]. This pozzolanic effect is quite different from that of coal fly ash. In fact, coal fly ash is essentially composed of spherical glass particles rich in silica and alumina. The products formed during the reaction with lime are mainly amorphous calcium silicate

hydrate (C–S–H), gehlenite hydrate (C_2ASH_8), calcium aluminate hydrate (C_4AH_{13}) and sometimes calcium carboaluminate and ettringite depending on the SO_4^{2-} content of the coal fly ash [16,17]. In the case of TFA, hydration studies on pastes of mixed TFA, lime and water have shown that the pozzolanic effect of TFA can be explained by the reaction between a calcium aluminosilicate phase contained in TFA and the calcium hydroxide. This widespread phase, occurring in two forms, a crystalline form (gehlenite) and an amorphous form, reacts with calcium hydroxide to form ettringite (in the case of TFA-A, the SO_4^{2-} content being significant) or calcium carboaluminate (in the case of TFA-B). These reactions are confirmed by the studies of the XRD patterns of 28-day-old CEMI-containing pastes (Fig. 3) and CEMIII-containing pastes (Fig. 4). The hydration of TFA-A-containing pastes leads to a significant increase in the formation of ettringite for the two types of binder. In both cases, a small quantity of anhydrite has still not reacted after 28 days. That could be worrying because it could react later to form delayed ettringite that could lead to expansion. In the case of TFA-B-containing pastes, the hydration products are
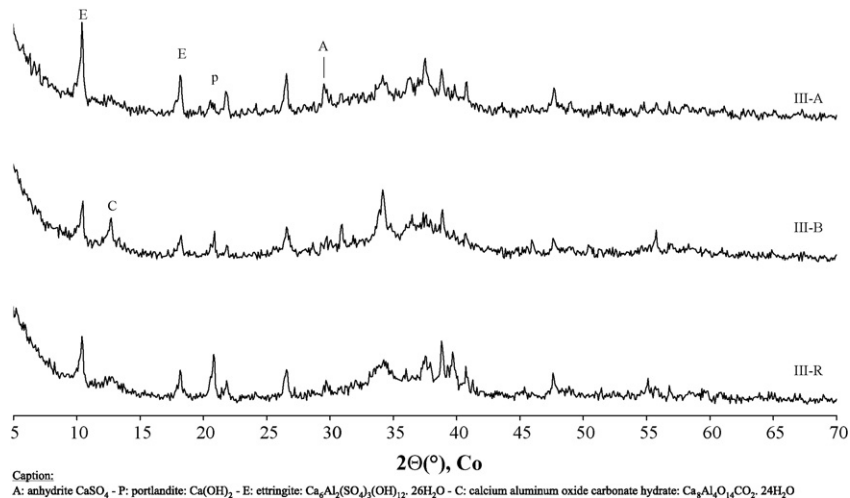

Caption:
A: anhydrite $CaSO_4$ - P: portlandite: $Ca(OH)_2$ - E: ettringite: $Ca_6Al_2(SO_4)_3(OH)_{12}.26H_2O$ - C: calcium aluminum oxide carbonate hydrate: $Ca_8Al_4O_{14}CO_2.24H_2O$

Fig. 4. XRD patterns of 28-day-old CEMIII pastes.

Table 5
Concentrations of leached elements (monolithic mortars)

Element	CEMI mortars			CEMIII mortars		
	I-R	I-A	I-B	III-R	III-A	III-B
Cr (µg/kg)	88	165	174	41	264	206
Ni (µg/kg)	14	28	31	16	23	17
Cu (µg/kg)	6	6	6	3	8	8
Zn (µg/kg)	<3	28	107	41	69	19
As (µg/kg)	1	3	1	0	7	5
Se (µg/kg)	<1	3	<1	<1	16	5
Mo (µg/kg)	2	3	1	1	17	4
Cd (µg/kg)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sb (µg/kg)	1	8	54	<0.1	4	79
Ba (µg/kg)	136	434	215	12	99	22
Pb (µg/kg)	<0.3	4	11	<0.3	<0.3	<0.3
pH	11.1	11.4	11.1	10.6	10.5	11.1
SF (g/kg)	1.81	3.24	3.41	1.57	3.17	2.51

different depending on the binder used. For the CEMIII, the hydration product is similar to that observed on a paste of mixed TFA-B, lime and water, i.e. a calcium carboaluminate. For the CEMI, new hydration products appear, like calcium aluminum oxide hydrates ($Ca_4Al_2O_7·xH_2O$ and $Ca_3Al_2O_6·xH_2O$). These hydrates normally form in CEMI type cement as the SO_4^{2-} content is not sufficient to form ettringite [16,17].

3.4. The environmental impact of TFA-containing mortars

The results of leaching tests are given in Table 5 for the test on monolithic mortars and Table 6 for those on crushed mortars. These results are the average of three replicates. The concentrations of the solutions were calculated versus the mass of solid (µg/kg). These two tests give an account of two types of scenario during the life cycle of waste-containing materials. On the one hand, the test on monolithic material permits an evaluation of the environmental impact of the polluted material during its normal service life. Since no quality criteria in terms of leaching from a monolithic material are currently available in Europe, the results of the leaching tests can be analyzed by comparing the results obtained with waste to those obtained with the reference mate-

rial. On the other hand, the test on crushed material shows what could happen at the end of the life of the material, for example after its destruction and its disposal in a landfill. So, to evaluate the environmental impact of TFA-containing crushed mortars, the results of leaching tests can be compared with the limit values for waste acceptable at landfills for inert waste according to the European landfill directive [18].

The potential of the mortar to retain pollutants in its structure can be evaluated by comparing the results of leaching tests on crushed and monolithic mortars. The leaching of elements from the monolithic mortars is always much lower than from the crushed mortars, except in the case of arsenic. The leaching of arsenic is influenced by the pH of the solution, as already observed by Van der Sloot [19]: the lower the pH (10.5–11.6 in monolithic mortars versus 11.7–12.4 in crushed), the higher the amount of arsenic leached.

The results on monolithic mortars show that the substitution of TFA in place of cement increases the release of harmful elements. This is the case for chromium in particular: the stabilization of chromium is less efficient when CEMIII is used, which is contrary to what was expected. The release of barium coming from the CEMI reference mortar is significant, which leads to a worse stabilization of this element for the mixtures I-A and I-B compared to the results of CEMIII mortars. The release of antimony is much more significant when TFA-B is introduced into mortar. This can be linked to the results of the leaching tests carried out on the two ashes [5]: TFA-B released much more antimony than TFA-A.

Contrary to observations for the monolithic mortars, the concentrations of leached elements from the crushed mortars are not always higher when TFA replaces a part of the cement. In fact, for the CEMI mortars, the concentrations of nickel, copper, zinc, selenium and barium are greater than or comparable to that obtained with TFA-containing mortar. The same tendency can be observed for CEMIII mortars, except as far as selenium is concerned. Three elements exceed the limit values for waste acceptable at landfills for inert waste. First, the soluble fraction of all the mixtures is higher than that recommended by the directive. This is probably due to the solubility of the Portlandite

Table 6
Concentrations of leached elements (crushed mortars)

Element	CEMI mortars			CEMIII mortars			Threshold limit for inert waste landfills
	I-R	I-A	I-B	III-R	III-A	III-B	
Cr (µg/kg)	307	508	517	143	567	875	500
Ni (µg/kg)	27	14	26	17	6	4	400
Cu (µg/kg)	25	17	25	11	8	22	2000
Zn (µg/kg)	205	181	316	65	9	41	4000
As (µg/kg)	1	1	3	2	3	5	500
Se (µg/kg)	92	63	82	25	40	44	100
Mo (µg/kg)	6	18	12	12	46	27	500
Cd (µg/kg)	<0.1	0.1	2	<0.1	1	1	30
Sb (µg/kg)	2	3	39	0.2	4	140	60
Ba (µg/kg)	6922	7297	5816	2082	747	451	20,000
Pb (µg/kg)	9	16	127	2	<0.3	6	500
pH	11.7	12.4	11.9	11.7	11.2	11.8	–
SF (g/kg)	20.5	19.6	19.5	13	6.33	5.57	4

$(Ca(OH)_2)$ contained in the cement paste. Second, the poor stabilization of antimony contained in TFA-B, already observed on monolithic mortars, is confirmed. CEMI stabilizes this element better than CEMIII (39 μg/kg for I-B; 160 μg/kg for III-B). Finally, the behavior of chromium is worrying in a perspective of reusing TFA in cement-based materials. Neither CEMI nor CEMIII is able to stabilize this element efficiently. The release of chromium from TFA-A is a little less than from TFA-B. Two reasons could explain this result. First, the leaching tests carried out on the ashes [5] have shown a strong difference between the two ashes: TFA-B releases much more chromium than TFA-A, which could be explained by the modifications of the stabilization process [5]. Second, TFA-B, being free of sulfate, leads to less formation of ettringite in mortars than occurs when TFA-A is used. Ettringite is known to be a host mineral able to fix harmful elements, and in particular heavy metal oxyanions like chromate, arsenate and selenate [20–23]. Even if ettringite can partially contribute to Cr immobilization, the results from the leaching test suggest a need to investigate specific treatment steps or mixture modifications aimed at a further reduction of Cr release. Many techniques exist to reduce the toxic, soluble form of chromium (Cr(VI)) into the non-toxic form (Cr(III)) by using reducing agents, e.g. H_2S, Al^0, $FeSO_4$ [24–27]. Further experiments in this sense will be necessary to improve the immobilization of chromium in MSWI fly ash with a view to safely reusing it in cement-based materials.

4. Conclusion

This second of two articles dealing with the utilization of MSWI fly ash in blended cement has studied the effects of the two variants of the stabilization process on the behavior of the TFA introduced in cement-based mortars. The modifications of the process have significant consequences on the water demand of TFA and the mechanical strength of ash-containing mortars. The increase of the fineness of TFA-B due to the modifications of the process increases its water demand, which was compensated for by using a superplasticizer. Moreover, TFA-B, free of metallic aluminum and sulfate, does not provoke any swelling in mortars, in contrast to TFA-A. So, TFA-B has a considerable activity in mortar whatever the cement used (CEMI and CEMIII), its activity indexes being higher than that of coal fly ash. This activity is present in the case of TFA-A, too, but it is hidden by the significant swelling of TFA-A-containing mortars. The two ashes have a pozzolanic effect that can be explained by the reaction with the calcium aluminosilicate phase contained in TFA and that was already pointed out in the first of these two articles. So, from a technological point of view, the modifications of the process are very efficient and produce an ash that can advantageously replace a part of the cement in cement-based material.

The study of the environmental impact of the ash-containing mortar must moderate these claims. The results of traditional leaching tests on monolithic and crushed mortars highlight a poor stabilization of some harmful elements such as antimony and chromium. For the latter, the use of cement rich in GGBFS (CEMIII) does not lead to the better stabilization expected. The

poor stabilization of chromium is worrying from the standpoint of safely reusing these ashes in cement-based materials and further experiments are necessary to find solutions to reduce the release of this harmful element. The reduction of chromium could be one of these solutions that should be investigated. Since neither adequate tests nor quality criteria to evaluate the pollutant potential of a waste with a view to its reuse exist, it is difficult to conclude on the environmental soundness of such reuse. New representative tests considering the reuse of waste instead of considering only its disposal in landfills need to be developed. Similarly, legal thresholds must be established to allow the classification of the waste for either reuse or disposal in a landfill. The establishment of these experimental tests and these legal thresholds must of course take into account the scenario considered. This notion of scenario constitutes one of the most recent evolutions of the standardization of the reuse of waste as it appears in the recent European standard EN 12920 [28].

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