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Recycling of municipal incinerator bottom ash as aggregate in hardened mortar: Comparison of the use of Portland cement and blast-furnace slag cement

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Abstract

Faced with the depletion of non-renewable natural resources worldwide, and considering the greenhouse gas emissions (CO_2) associated with construction, the use of alternative granular materials has become a viable option in the construction industry. In this investigation, the partial and/or total replacement of natural sands with non-hazardous waste incineration bottom ash (MSWIBA) sands was studied for the production of cement mortars using two types of cement, namely CEM I Portland cement and CEM III blast furnace slag cement. The substitution rates were 50%, 75%, and 100% by volume. Mechanical and environmental properties were evaluated for the mortars containing MSWIBA sands. The results show that the uniaxial compressive strengths for the 50% V/V substitution rate reach average values of 50 MPa after 180 days of moist curing for CEM III cement. For the 75% and 100% V/V substitution rates, the average values are around 40 MPa. In general, it is observed that CEM III cement yields better mechanical results. Leaching tests conducted on the MSWIBA sand particles and on the mortars containing 100% MSWIBA sands demonstrated that there is no health risk or hazard associated with the use of MSWIBA as a substitute for natural granular materials in the construction sector.

Keywords: MSWI bottom ash; Carbon footprint; Leaching test; Uniaxial compressive strength; Blast-furnace slag cement

1. Introduction

The use of aggregates represents a significant portion in the civil construction sector. According to the National Union of Quarrying and Gravel Industries, out of the 322 million tons of aggregates (production and importation) produced in France in 2016, 33% were dedicated to the production of hydraulic concrete (UNPG, 1999). In order to preserve non-renewable natural resources and reduce the carbon footprint of constructions in general, the use of recycled aggregates has become an increasingly popular and sustainable solution in the construction sector in European countries. Statistics show that the utilization rate of recycled aggregates has been continuously increasing in recent decades. For example, in France, this rate increased from 19.7% in 2008 to 23.1% in 2014 (UNPG, 1999).

Recycled aggregates mainly consist of slag, shale, materials from demolition (GBR), but also include aggregates derived from the incineration of household and similar waste. This category of recycled aggregates, also known as municipal solid waste incineration bottom ash (MSWIBA), is a significant asset in the construction sector as it represents a substantial resource in Europe. According to the Confederation of European Waste-to-Energy Plants (CEWEP), approximately 93 million tons of household and similar waste were treated in incineration plants in Europe in 2016,

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producing around 19 million tons of MSWIBA. Of this amount, 80-85% comprises the mineral fraction, 10-12% consists of metals (such as steel), and 2.5% consists of non-ferrous metals (CEWEP, 2019). Before being used in construction or in the production of cementitious materials as an alternative secondary granular material replacing natural aggregates, MSWIBA must undergo a phase of metal particle recovery (iron, aluminum, zinc, etc.) and a maturation phase to remove impurities and obtain the purest possible mineral fraction (Amorce, 2012).

The main avenues for valorizing MSWIBA in European countries as secondary construction materials include: (a) the use of granulates in road construction (Becquart et al., 2009) and concrete products (Bertolini et al., 2004) (in Belgium, the Netherlands); (b) road sub-base and embankment applications, as well as road construction (in Denmark, France, Germany, Italy, the Netherlands, Portugal, Spain, and the UK) (Van Brecht & Konings, 2011; Chang et al., 1999; Cioffi et al., 2011; Forteza et al., 2004; Schreurs et al., 2000).

Chemical reactions that can cause swelling pathologies may occur when MSWIBA is used as aggregates in the production of cementitious materials, including:

- Alkali-silica reaction (Müller & Rübner, 2006 ; Rübner et al., 2008);
- Aluminum gel formation (Pera et al., 1997; Pecqueur et al., 2001);
- Secondary ettringite formation (Müller & Rübner, 2006).

Table 1 Mechanical properties of hardened mortar containing bottom ash (Saikia et al., 2015; Ferraris et al., 2009)

Granular Fraction	Treatment applied	Ratio substitution	Ration W/C	Compressive strength [MPa]	
				28 d	**60 d**
0.1 -2 mm	Without treatment	0%	0.5	54	57
0.1 -2 mm	Water	25% (m/m)		56%*	58%*
0.1 -2 mm	Na2CO3 solution (0.1-0.25)	25% (m/m)		56%*	58%*
0.1 -2 mm	Heating (675°C)	25% (m/m)		65%*	
0.1 -2 mm	Na2CO3 solution (0.1-0.25) & heating (675°C)	25% (m/m)	0.5	55%*	56%*
0.1 -2 mm	Heating (675°C) & Na2CO3 solution (0.1-0.25)	25% (m/m)	0.5	75%*	77%*
0.1 -2 mm	Superplasticizer Heating (675°C) & Na2CO3 solution (0.1-0.25)	25% (m/m)	0.5	92%*	94%*
0-5 mm	Heating (1450°C) Crushing Sieving	0%	0.6	44.7	45.8
		25% (v/v)		40.0	42.7
		50% (v/v)		35.7	38.3
		75% (v/v)		33.6	34.8
		100% (v/v)		30.7	32.2

(*) The table represents the percentages of uniaxial compressive strength compared to the reference mortar without substitution.

To prevent these reactions from occurring in cementitious materials, treatments are applied to the MSWIBA to bring their intrinsic properties as close as possible to those of natural aggregates commonly used in concrete production. These treatments can include physical and mechanical processes (Grosso et al., 2011; Bourtsalas, 2012), chemical treatments (Saikia et al., 2015; Sorlini et al., 2011) and thermal treatments (Grosso et al., 2011), which can enhance the quality of the mineral fraction of MSWIBA.

Based on the literature, several studies have demonstrated that MSWIBA can be used as a substitute for natural aggregates in the production of mortars (Saikia et al., 2015; Al-Rawas et al., 2005; Minane et al., 2017) and concrete (Pera et al., 1997; Jurič et al., 2006; Courard et al., 2002; Ferraris et al., 2009; Keppert et al., 2012; Siddique, 2010; Tay et al., 1982; Van Wegen et al., 2013). The findings of these studies indicate two trends when MSWIBA is used as a replacement for natural aggregates in cementitious materials. On one hand, the mechanical strengths of cementitious materials containing MSWIBA are generally lower compared to those of standard concrete (Pera et al., 1997). As a result, their use is limited to less stressed parts of structures (BM, 1986; Qiao et al., 2008; Kuo et al., 2013). On the other hand, it has also been observed that the mechanical strengths of concrete can be equal to or even higher than those of standard concrete (Nielsen et al., 2009). These mechanical results obtained from cementitious materials containing MSWIBA are influenced by various treatments applied to the granular materials, both in the fine and coarse fractions.

Table 1 provides a non-exhaustive list of the mechanical properties of cementitious materials containing MSWIBA fractions (0-5 mm) as a replacement for natural sand.

Based on Table 1, the observations show that the mechanical performance of cementitious materials is improved depending on the type of treatment applied (chemical and/or thermal), especially on the fine fractions (0.1-2 mm).

This investigation is focusing on the 0-2 mm fraction of MSWIBA because it contains a higher concentration of pollutants and metallic particles (Al, Z, etc.) compared to the coarse fractions (> 6 mm) [Muchova, 2010; Tang et al., 2016). Therefore, it would be wise to investigate the physical and mechanical behaviours of mortars containing this granular fraction of MSWIBA and evaluate the encapsulation effect of MSWIBA in the two selected cement matrices through an environmental analysis.

This paper is aiming to assess the mechanical and environmental properties of hardened mortars containing 0-2 mm bottom ash sand fractions as a partial and/or total replacement of natural sand in two distinct cement matrices: ordinary Portland cement and blast furnace slag cement.

2. Material and methods

2.1. Bottom ash

The selected MSWIBA for this research, after undergoing the conventional technical treatment used in waste incineration plants, went through successive stages of selective grinding to further separate the mineral fraction and metallic particles. The ferrous and non-ferrous metals were recovered using magnetic technique, as well as specific Foucault current separators of the NES 4T type. The two MSWIBA samples are labelled as MAC-A and MAC-S, originating from the Île-de-France region and the Hauts-de-France region, respectively.

These two granular fraction materials with a size range of 0-2 mm were sampled according to the EN 932-2 standard (1999) prior to the physical, chemical, and environmental property assessments.

2.1.1. Physical characterization

Table 2 Physical parameter of sampled incinerator bottom ash

Test	**Ref. meth.**	**Results**	
		MAC-A	**MAC-S**
Grain size distribution	NF EN 933-1 (2012)	Well-graded	Well-graded
Fine content	NF EN 933-1 (2012)	6.2	4.3
Specific gravity	Pycnometer helium	2.6	2.6
Apparent gravity	NF EN 1097-6 (2014)	1.9	2.0
Water absorption (%)	NF EN 1097-6 (2014)	7.5	9.4
Loss on ignition (%)	NF EN 1744-7 (2012)	4.3	4.3
Morphology grain	NF EN 933-6 (2014)	Crushed	Crushed

According to the literature [Crillesen, 2006; Crillesen et al., 2006; Ginés et al., 2009; Filipponi et al., 2003; Becquart, 2007; Bröns-Laot, 2002), raw MSWIBA appears as heterogeneous, dark gray slag with the presence of ferrous and non-ferrous particles and unburned materials. The choice of magnetic separators (for removing ferrous and non-ferrous metals) has an impact on the physical characteristics of the processed materials. Similarly, the presence of unburned materials is influenced by the chosen incineration process. In general, it is found that MSWIBA has a loss on ignition value ranging from 2.5% to 9%, an absolute density ranging from 2.5 to 2.8, and absorption coefficients ranging from

5% to 10%. The morphology of the aggregates was estimated through the angularity test according to the applicable standard NF EN 933-6 (2014), and the physical parameters of the two selected MSWIBA are summarized in Table 2.

The physical properties of the two selected MSWIBA fall within the ranges of values found in the literature. Additionally, the loss on ignition values remains below the regulatory limit set by French regulations (5% SETRA, 2012). The absorption rates of the aggregates are relatively high compared to natural aggregates of the same particle size fraction (Dupain & Saint-Arroman, 2009). Furthermore, the angularity test shows that the grains have a crushed type, which is likely to have an impact on the rheology of the fresh cement paste. The grain size distribution curves of the two selected MSWIBA (MAC-A and MAC-S) and the range defined by the standardized sand (0-2 mm) used in this investigation are presented in Figure 1. It can be observed from this graph that both grain size distribution curves are well-graded and follow the same trend as the lower limit of the standardized sand. However, while the standardized sand does not contain fines, the two MSWIBA samples contain 6.2% and 4.3% of fine elements, respectively. Therefore, an additional water content may be necessary compared to the standardized sand during mortar preparation.

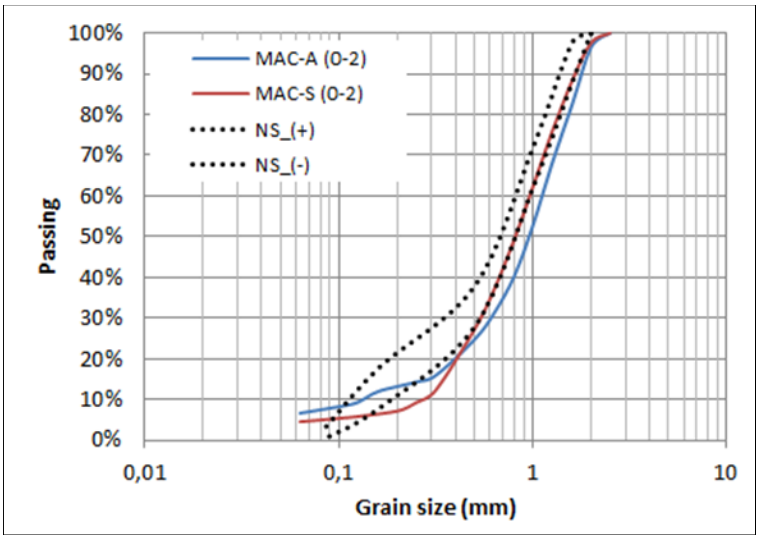

Figure 1 Grain size distribution of sampled bottom ash

2.1.2. Chemical characterization

Table 3 Average presence of non-oxygen elements in sampled bottom ash

Element	MAC-A	MAC-S	Reference [Crillesen, 2006]
	Wt %		
Si	18.4	18.7	16.8 – 27.4
Ca	16.3	15.6	5.1 – 10.3
Fe	2.4	2.0	2.1 – 11.5
Mg	1.2	1.9	0.2 – 1.2
K	1	1.2	0.7 – 1.2
Al	4.4	4.4	3.4 – 6.5
Na	3.4	3.2	2.0 – 4.8

According to the literature, the chemical and mineralogical composition of MSWIBA can be influenced by the composition of the waste prior to incineration (Rendek et al., 2007). However, the minerals present in MSWIBA can be categorized into three groups: those that are present in the incinerated waste and remain unaltered by the incineration process, minerals formed during incineration, and minerals that form immediately after exiting the furnace during cooling and/or maturation phases. Generally, the minerals found in most MSWIBA produced in European countries include quartz (SiO2), lime (CaO), corundum (Al2O3), hematite (Fe2O3), and iron oxides (Na2O) (Pera et al., 1997; Al-Rawas et al., 2005; Crillesen, 2007; Ginés et al., 2009; Del Valle-Zermeño] et al., 2013).

In this research, the chemical composition of MSWIBA was determined using X-ray fluorescence analysis. The semi-quantitative analysis program on the Bruker Axs S4 Pioneer X-ray fluorescence spectrometer was employed. The chemical composition of the two-selected MSWIBA in this study are presented in Table 3.

The main elements that make up the two MSWIBA samples fall within the range of values found in the literature, except for the higher concentrations of calcium. Although the two MSWIBA samples were collected from two different regions in France, where dietary habits may differ (leading to variation in waste composition entering the incinerator), it is observed that the chemical element values are quite similar.

The mineralogical analysis of MSWIBA was performed using X-ray diffraction (XRD) analysis techniques. The equipment used was a D5000 diffractometer from Siemens. The results of the XRD diffractograms for the two MSWIBA samples are shown in Figure 2.

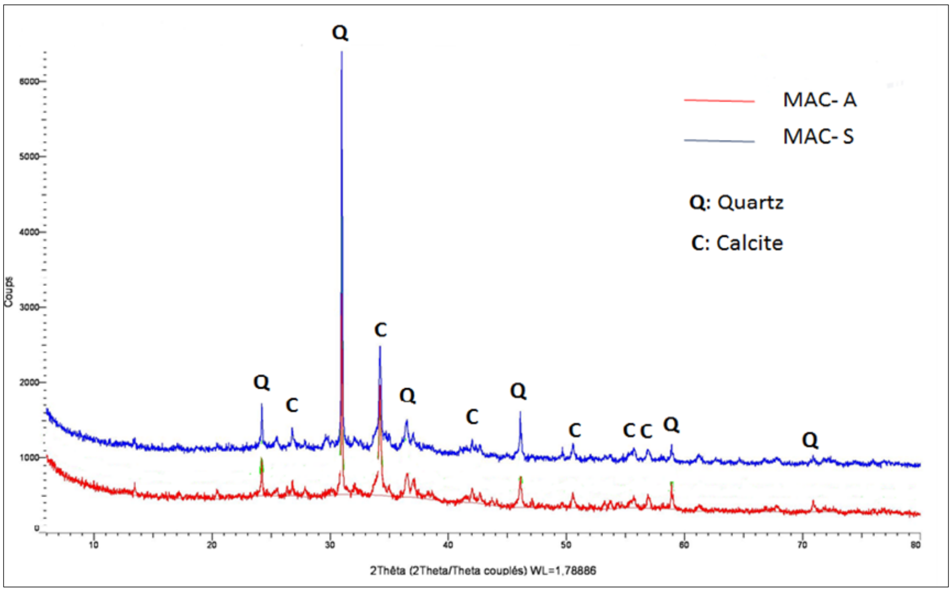

Figure 2 Diffractometer of sampled incinerator bottom ash

XRD analysis revealed that the main identifiable mineral phases in the materials are quartz and calcite. Additionally, there are also other mineral phases present in smaller proportions, such as iron oxides and corundum, which are not easily detectable in this diffractogram. X-ray fluorescence analysis was able to confirm the presence of all the chemical elements in the MSWIBA samples.

2.1.3. Environmental characterization

The environmental characterization of the studied incineration bottom ash was carried out through leaching tests on grain particles. These tests assess the potential release of heavy metals present in the materials. The analysis was conducted on the bottom ash particles in accordance with the French standard NF EN 12457-2 (2002). Table 4 presents the average values from three experimental measurements. The leachate concentrations are compared to the leaching limit values according to the European Directive, which classifies waste into three categories: inert, non-hazardous, and hazardous (ALS France Environnement, 2020).

Table 4 Leaching tests on BA samples and limits set in EU legislation (mg.kg-1)

Element	MAC-A	MAC-S	Threshold value inert wastes	Threshold value non-hazardous wastes
	0–2 mm	0-2 mm	Set by EU (L/S=10)	Set by EU (L/S=10)
pH	9.9	9.3	-	>6

As	<0.1	<0.1	0.5	2
Cd	<0.002	<0.002	0.04	1
Cr total	<0.01	<0.01	0.5	10
Cu	1.0	1.1	2	50
Mo	<0.1	<0.1	0.5	10
Ni	<0.02	<0.007	0.4	10
Pb	<0.04	<0.04	0.5	10
Sb	<0.1	<0.1	0.06	0.7
Se	<0.1	<0.1	0.1	0.5
Zn	<0.02	<0.02	4	50
Chloride	2830	3130	800	15000
Sulfate	7700	9740	1000	20000

The leachate concentrations of both MSWIBA samples are below the limit values set by the European Directive (Table 4), except for sulphates and chlorides, which exceed the limits for inert waste category. Therefore, the granular materials are classified as non-hazardous waste according to the European regulations on waste status.

The very high concentrations of sulphate and chloride compared to the inert waste class reveal that the maturation period of the MSWIBA, which averaged 4 months, was not sufficient to significantly reduce the sulphate and chloride content below the recommended limit for inert waste. Accelerated carbonation, a method not commonly used in waste incineration plants in Europe, is a rapid solution to reduce the pollutant potential of MSWIBA, especially the soluble fraction (Arickx et al., 2006). The leaching tests conducted on the aggregates of MSWIBA indicate that the materials do not pose a direct threat to the environment and human health, although they may not fully represent the conditions under which the material is actually used.

2.2. Sand

The natural sand used in the various formulations complies with European regulations and is a standardized sand consisting mainly of silica, with a content of over 95% (Société Nouvelle du Littoral, 2015).

2.3. Cement

Two types of cement were used for the mortar formulations: CEM I Portland cement, commonly used in the construction industry, and CEM III blast furnace slag cement, known for its low environmental impact (NF EN 197-1, 2012). The characteristic compressive strengths at 28 days of curing are 61 MPa and 58 MPa, respectively, for CEM I and CEM III. CEM I cement is composed of 97% clinker, while CEM III cement consists of 54% clinker and 43% blast furnace slag. Table 5 presents the chemical composition of these two cements.

Table 5 Chemical analysis of cements

	CEM I	**CEM III**
Elements	Wt (%)	Wt (%)
O	41.0	41.7
Ca	42.4	34.8
Si	8.1	12.5
Al	2.3	4.6
S	1.69	1.1
K	0.9	0.6

Mg	0.5	2.6
Na	0.3	0.3
Ti	0.2	0.4
P	0.1	Traces

2.4. Superplasticizer

In order to achieve consistent workability in all mortar formulations, the decision was made to use a superplasticizer called "MasterGlenium SKY 537." This superplasticizer was only used in mortars containing MSWIBA sands due to their porosity and the presence of fines compared to the standardized sand used. However, the saturation dosage of the superplasticizer was determined in order to select a value applicable to all formulations. Two methods were employed to determine the saturation dosage of the superplasticizer: the spread on the shaking table method according to the NF EN 1015-3 standard (1999) and the slump test using the MBE cone as described in (Schwartzentruber & Catherine, 2000). The experimental setup for measuring the slump using the MBE cone is shown in Figure 3.

A. Slump test with MBE Cone B. Flow test with shaking table

Figure 3 Experimentation measurements of saturation dosage of the superplasticizer

The saturation dosages for the MAC-A and MAC-S mortar formulations are shown in Figure 4.

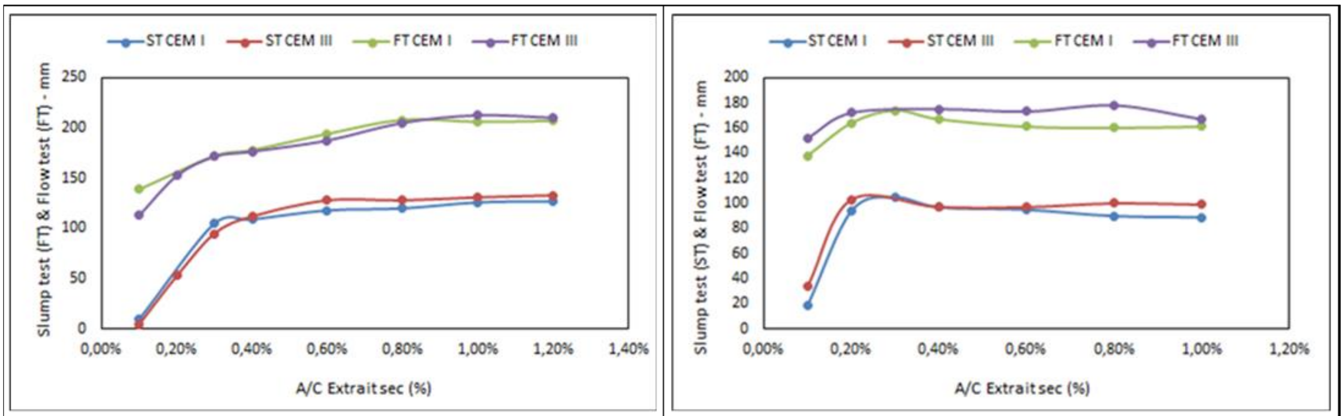

Figure 4.a MAC-A Mortars	Figure 4.b MAC-S Mortars

Figure 4 Slump and flow Measurements on the Formulations

From Figure 4, it can be observed that the saturation dosages for the MAC-A and MAC-S bottom ash sands are 0.8% and 0.4% dry extract by weight of cement, respectively, regardless of the two types of cement used. For this experimental campaign, the adopted value for the admixture is 0.3% for all formulations containing bottom ash sands, in order to prevent the occurrence of segregation phenomena observed after the saturation dosage of the superplasticizer.

2.5. Mortar production and testing

The preparation of cement mortars was carried out in accordance with the NF EN 196-1 standard (2016). Three types of formulations were performed: a reference mortar containing entirely standardized sand, and two mortars containing the MAC-A and MAC-S bottom ash sands, respectively, in partial and/or total substitution of the standardized sand. Due to the differences in actual bulk densities between the bottom ash sands (averaging 2.0 g/cm3) and the standardized sand (2.7 g/cm3), the substitution of the standardized sand with the bottom ash sands was done in volumetric proportions. The different volumetric substitution rates are approximately 50%, 75%, and 100% for each mortar containing the MSWIBA, aiming to maximize the utilization of bottom ash sands in cement applications.

Seven formulations were produced and Table 6 presents the composition of the mortars based on standardized sand and bottom ash sands. After mixing, the fresh mortar was placed in polystyrene prism molds with geometric dimensions of 40 mm × 40 mm × 160 mm in two equal layers. Each layer was compacted using a vibrating table to ensure proper distribution of the mortar in the mold. After filling the second layer of mortar, the specimens were covered with plastic film and placed in a curing room (T=20±°C and RH≥80%). The samples were demolded after 24 hours and then immersed in water basins for the entire curing period. To prevent potential contamination of the samples during the wet curing phase, the specimens were kept in separate covered water basins based on the origin of the bottom ash and the type of cement used.

Table 6 Composition of mortars based on standardized sand and bottom ash sands

Sample label	**NS**	**MAC-A**			**MAC-S**		
Ratio	**0%**	**50%**	**75%**	**100%**	**50%**	**75%**	**100%**
E/C	0.5	0.58	0.62	0.66	0.6	0.66	0.7
Cement mass (g)	450	450	450	450	450	450	450
Sand mass (g)	1350	675	337.5	0	675	337.5	0
BA mass (g)	0	475	712.5	950	500	750	1000
Absorption water (g)	0	35.6	53.4	71.3	46.8	70.2	93.6
Superplasticizer liquid mass (g)	0	6.75	6.75	6.75	6.75	6.75	6.75
Water mass (g)	225	219.6	219.6	219.5	219.6	219.6	219.6

2.6. Mechanical characterisation

The uniaxial compression tests on the prepared mortars were conducted at 7, 28, and 180 days of wet curing using an Instron electromechanical press with a maximum load capacity of 150 kN. The reported mechanical strength values are the averages obtained from five measurements.

2.7. Environmental behavior

Environmental characterization was performed on both the reference mortars and the mortars prepared with 100% bottom ash sands, as it best reflects the conditions of incorporating MSWIBA into the cementitious matrix. The choice was made to focus on this substitution rate because it represents the most unfavorable scenario for a high potential of pollutant release into the environment, compared to mortars prepared with 50% and 75% bottom ash sands. This environmental analysis aimed to determine the intrinsic pollutant content and the leachable metals in the monoliths prepared with bottom ash sands (RECORD, 2004; RECORD, 2015).

The leaching tests were prepared following the protocol described in the NF EN 12457-2 standard (2002). The materials, previously dried in an oven (105°C) until reaching a constant mass, were crushed to a diameter smaller than 4 mm. Then, the material was placed in a jar containing demineralized water with a liquid-to-solid ratio (L/S) of 10 and agitated (rotated) around a horizontal axis for 24 hours at a speed of 11 revolutions per minute. The leachates collected after 24 hours were filtered (0.45 µm filter) and analysed using inductively coupled plasma (ICP) spectroscopy. The concentrations obtained for the different fractions of incineration bottom ashes were compared to the allowable threshold values for the "V1" and "V2" categories set by the ministerial order of November 18, 2011 (AM, 2011; CEREMA, 2014). The "V1" and "V2" categories refer to the classes of use for road works, which can utilize incineration bottom ashes as secondary granular materials and served as a reference for the environmental classification of MSWIBA (AM, 2011). Table 7 presents the different standards used in the laboratory for the determination of pollutant elements.

Table 7 Analysis methods for environmental characterization

Pollutants tested	Analysis method
TOC	NF EN 13137
BTEX	NF ISO 22155
PCB	NF EN 15308
Hydrocarbon	NF EN 14039
Preparation of leaching tests	NF EN 12457-2
Leachable metals	NF EN 17294-2

3. Results and discussion

3.1. Compressive strength

The results of uniaxial compression for the MAC-A and MAC-S mortars, as well as for the mortars containing standardized sand, are reported in Figures 5 and 6.

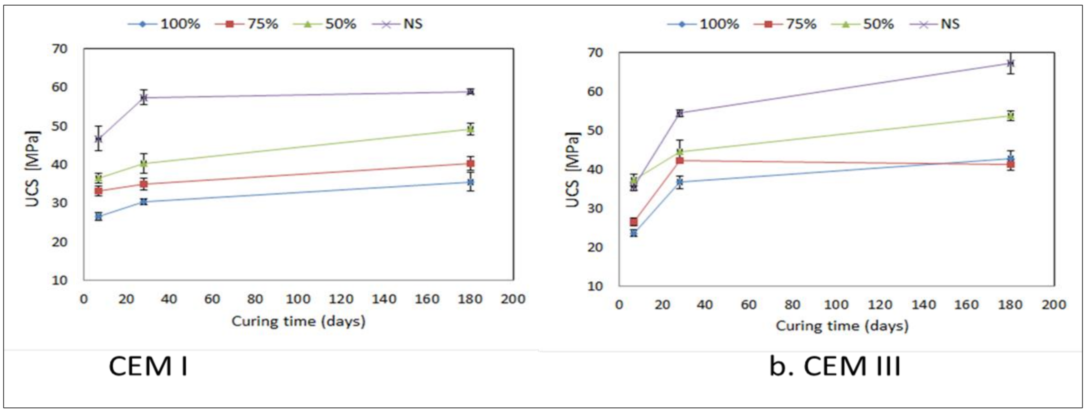

Figure 5 Compressive strength of MAC-A CEM I and MAC-A CEM III mortars

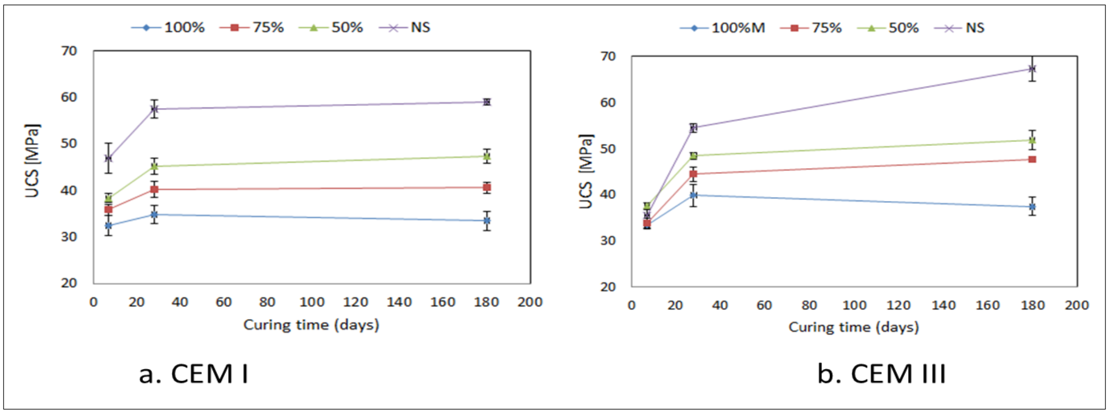

Figure 6 Compressive strength of MAC-S CEM I and MAC-S CEM III mortars

Observations made on these graphs are described as follows:

- The mechanical strengths of the reference mortars containing CEM I show similar ranges between 28 and 180 days, while an average increase of about 20% is observed for the reference mortars prepared with CEM III cement. This result can be explained by the pozzolanic activity of the blast furnace slag and the fineness of the cement particles. The Al/Si ratio for CEM III cement, which is 0.37, is higher than that of CEM I cement (0.28). The presence of alumino-silicate compounds in CEM III cement allows them to react with water in the presence of an alkaline activator, namely free hydrated lime, to form more hydrates following the two equations:

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow CaO.SiO_2.H_2O \quad \text{……………….(1)}$$

$$Ca(OH)_2 + Al_2O_3 + H_2O \rightarrow CaO.Al_2O_3.H_2O \quad \text{…………….(2)}$$

The same observation is made for the mortars containing treated bottom ash sands.

- The uniaxial compressive strengths of the mortars decrease with an increasing replacement rate of treated bottom ash sands for standardized sand in the mixtures. This observation holds true for both types of treated MSWIBA used. This decrease in strength can be attributed to two factors. Firstly, the densification of the mortars is less significant for the mortars containing treated bottom ash sands compared to those containing standardized sand (bulk density of standardized sand is 2.64, while bulk density of treated bottom ash sand is 1.95). Secondly, the decrease in strength can also be attributed to the higher water-to-cement ratio (W/C ratio) in the mortars containing treated bottom ash sands (0.6 - 0.7) compared to the mortars containing standardized sand (0.5). The loss of water during the curing period leads to a significantly higher porosity in the mortars containing treated bottom ash sands compared to the reference mortars, resulting in a decrease in strength.
- The complete substitution of reference sand with treated bottom ash sands results in a decrease in uniaxial compressive strengths of the mortars ranging from 26% to 45%, regardless of the type of treated bottom ash sand or cement used. For a substitution rate of 75%, the decrease in mechanical strength is approximately 30%, while for a partial substitution rate of 50%, the average mechanical strengths of the mortars are reduced by about 20% compared to the reference mortars. These results indicate that treated bottom ash sands can be a viable alternative for low-stress structures and, consequently, can be used in the production of lightweight concrete.

In order to compare the results obtained in this experimental campaign with mortars containing treated bottom ash sands processed by other methods (chemical and/or thermal) found in the literature, it is more appropriate to evaluate the percentage decrease in mechanical strength based on the substitution rate. Figure 7 shows the percentage decrease in uniaxial compression at 7 and 28 days of curing for the different mortar formulations compared to the reference formulation. This value is obtained by dividing the mechanical strength of the mortar at a given time by the mechanical strength of the reference mortar at the same curing time.

Based on Figure 7, it can be observed that the mechanical strengths of the mortars with treated bottom ash sands and CEM III cement yield better results compared to those prepared with CEM I cement. At 28 days of curing, the MAC-S mortars with CEM III cement represent 73.1%, 81.5%, and 89% of the reference value, respectively, for substitution rates of 100%, 75%, and 50%. These results are significantly higher than the values reported in the work of Ferraris et al. (2009) with the same volumetric substitution rates when the treated bottom ash sands were processed using thermal methods (vitrification at 1450°C) and mechanical methods (grinding and sieving). Similar observations can also be made for the values found in the literature (Table 2), although the substitution rates, which are relatively lower than those adopted in this experimental campaign, are reported in mass proportions (Saikia et al., 2015). These results indicate that the fraction of treated bottom ash sands, despite a slight decrease in mechanical strength values, can be used for partial or complete substitution of natural aggregates in the civil construction sector, especially for low-stress structures or lightweight concrete applications. Potential applications include road curbs, pedestrian pavements, and other roadside structures, which can benefit from the use of treated non-hazardous incineration bottom ash sands. However, an environmental study should be conducted to assess the potential release of treated bottom ash sands, encapsulated within the cementitious matrix, into the immediate environment to avoid any health risks to nearby populations.

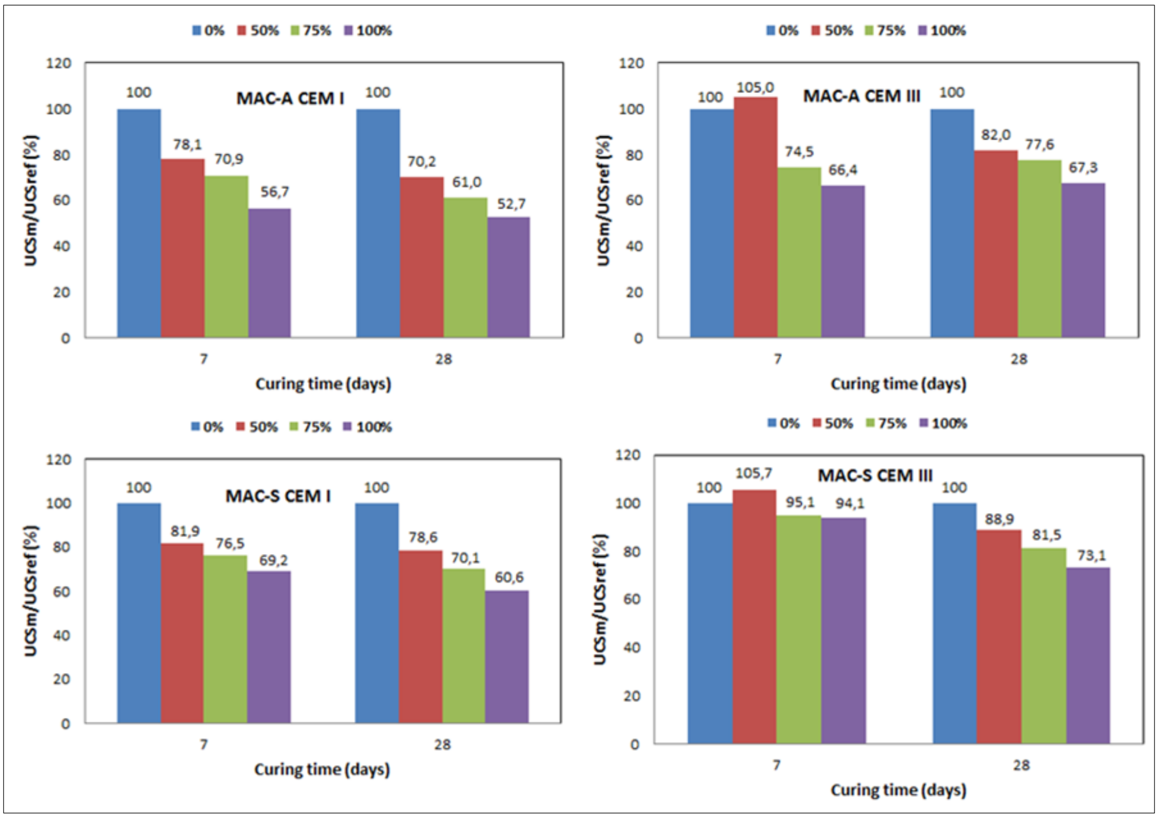

Figure 7 Percentage decrease in mechanical strength as a function of curing time

3.2. Environmental behavior

Table 8 Results of leaching values on the monoliths containing MSWIBA

Pollutants	NS	NS	MAC-A	MAC-A	MAC-S	MAC-S	Threshold value	
	CEM I	CEM III	CEM I	CEM III	CEM I	CEM III	V1	V2
pH	12.65	12.65	12.60	12.40	12.60	12.25	-	
TOC	4.0	4.0	15.0	12.0	15.0	15.0	30 g/kg	
BTEX	<0.60	<0.60	<0.60	<0.60	<0.60	<0.60	6 mg/kg	
PCB	<0.30	<0.30	<0.30	<0.30	<0.30	<0.30	1 mg/kg	
Hydrocarbons	<25	<25	<25	<25	26	33	500 mg/kg	
HAP	<1.60	<1.60	<1.6	<1.6	<1.6	<1.6	50 mg/kg	
Dioxins and furans	0.0	0.0	1.8	1.7	4.7	4.4	10 ng I-TEQ/kg	
Leachable metals	(mg/kg)						V1	V2
As	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.6	0.6
Cd	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.05	0.05
Cr total	0.10	<0.05	0.06	<0.05	0.07	0.09	2	1
Cu	<0.05	<0.05	0.67	0.81	0.77	0.95	50	50
Hg	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	0.01
Mo	0.06	0.07	0.11	0.28	0.13	0.39	5.6	2.8
Ni	<0.05	<0.05	0.06	0.07	0.06	0.08	0.5	0.5

Pb	0.16	0.12	1.25	0.79	0.65	0.56	1.6	1.0
Zn	<0.5	<0.5	0.80	0.81	0.70	0.58	50	50
F	1.7	1.8	1.2	1.5	1.4	1.8	60	30
Chloride	91	88	917	873	980	1188	10000	5000
Sulfate	67	19	16	43	18	84	10000	5000

Table 8 presents a summary of the results from the environmental study on cement mortars containing treated bottom ash sands. The reference values (cement mortars without bottom ash sands) are also included in this table, along with the permissible limits for the use of MSWIBA in the road construction sector. It could be observed that concentrations of elements such as Total Organic Carbon, BTEX, PCB, hydrocarbons, PAHs, dioxins and furans remain well below the permissible threshold values set by the ministerial order of November 18, 2011 (AM, 2011).

Regarding leachable metals, it is observed that the leachate concentrations of the analysed metals remain below the permissible values for classes V1 and V2. These results demonstrate that MSWIBA are effectively immobilized within the cementitious matrix, and the risk of leaching is no longer a concern. Therefore, phenomena such as groundwater contamination and other environmental threats to biodiversity are unlikely to occur due to the treatment applied to MSWIBA. Consequently, incineration bottom ash sand fraction could be a viable alternative to natural materials in the production of concrete

4. Conclusion

This paper focused on investigating the use of treated non-hazardous incineration bottom ash sands as a replacement for natural sand in two distinct matrix cementitious: Portland cement of type CEM I and blast furnace slag cement of type CEM III. Two types of MSWIBA from the Hauts de France and Ile-de-France regions were selected for this investigation. The intrinsic characteristics (physical, chemical, mineralogical, and environmental) of the MSWIBA were presented. The standardized sand with a particle size of 0/2 mm (reference sand) was partially and completely replaced by MSWIBA sands of the same fraction at volumetric proportions of 50%, 75%, and 100%.

The mechanical and environmental properties of the monoliths containing treated MSWIBA sands were analyzed at different curing times. It is found that:

- The results of mortars containing treated MSWIBA sands and prepared with CEM III cement are better than those of mortars prepared with CEM I Portland cement.
- The uniaxial compressive strengths of all formulations of mortars containing treated MSWIBA (CEM I and CEM III) continue to increase beyond 28 days. This observation is also made for the reference mortar (without MSWIBA) based on CEM III cement, but not for the reference mortar based on CEM I (where the curve remains constant from 28 days to 180 days). This can be explained by the pozzolanic reaction that occurs between the aluminium components present in the MSWIBA and the CEM III cement with the free hydrated lime to form additional hydrates and thus increase the mechanical strengths.
- The partial and/or total replacement of natural sand with treated MSWIBA sand results in a decrease in the uniaxial compressive strengths of cement mortars. This decrease ranges from 11% to 18% for 50% V/V replacement, from 18% to 22% for 75% V/V substitution, and from 27% to 33% for complete replacement at 100% V/V. These results indicate that the treated MSWIBA sands can be partially substituted up to 75% by volume for the production of concrete used in lightly loaded structures. Furthermore, total replacement (100% V/V) of natural aggregates with treated MSWIBA sands can be done only for applications such as concrete pavers for pedestrian traffic and road curbs.
- The environmental assessment through leaching tests conducted on the MSWIBA sands as well as on the cement mortars containing MSWIBA sands showed that the concentrations of all leachable metals (As, Cr, Cu, Pb, Zn, etc.) and other pollutants (PAHs, BTEX, COD, dioxins, and furans) remain below the permissible threshold values set by the French ministerial order of November 18, 2011, which regulates the use of secondary granular materials in the road construction sector. Based on this analysis, it can be concluded that there is no health risk to the population or environmental threat associated with the use of treated MSWIBA sands with a particle size of 0/2 mm in the production of concrete.
- Considering the mechanical and environmental results of cement mortars containing treated MSWIBA, the choice leans more towards the use of CEM III cement, which is composed of blast furnace slag. This cement, with its low environmental impact due to its composition, not only provides better mechanical strengths at

longer curing times but also contributes to reducing the carbon footprint of constructions compared to Portland cement, which emits a larger amount of CO_2 into the environment

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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