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Upgraded mineral sand fraction from MSWI bottom ash: an alternative solution for the substitution of natural aggregates in concrete applications

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Abstract

This paper presents the results of an experimental investigation on the substitution of natural sand by municipal solid waste incineration (MSWI) bottom ash in concrete applications in order to preserve non-renewable natural resources and then, reduce the carbon footprint of buildings sector. First of all, physical, chemical and leaching test have been performed on upgraded MSWI bottom ash and the obtained results were compared to natural sand usually used in France in concrete applications. In the second time, a preliminary campaign carried out by utilizing 100% MSWI bottom ash 0-2 mm for the substitution of natural sand in the mortar applications. Physical characterization revealed that grain size distribution and specific gravity of MSWI bottom ash are similar to natural sand identified. However, water absorption content (W_{Ab} equal to 7.50%) of bottom ash is higher than natural sand. In order to improve the workability of mixing, a superplasticizer has been used at 0%, 1.5%, 2% and 3% by weight of cement. After 14 days of curing, compressive and flexural strengths were performed on hardened samples. Results showed compressive strength of bottom ash samples ranging from 19.4 MPa (without superplasticizer) to 33.3 MPa (3% of superplasticizer), following a linear trend while flexural strength ranging 4.7 MPa to 5.4 MPa. No health threat has been detected for the MSWI bottom ash 0-2 mm fraction and it was categorized as non-hazardous waste according to European legislation of waste. Study developments are currently oriented towards the analysis of physical, mechanical and thermal properties of concrete containing bottom ash and durability assessment.

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Keywords: MSWI bottom ash; upgraded mineral sand; concrete .

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1. Introduction

According to the French National Union of aggregates producers, more than 350 million of tons of aggregates are produced each year in France [1]. Unfortunately, this large quantity of aggregate does not cover the supply needs in civil construction. In order to preserve non-renewable natural resources and to reduce the carbon footprint of building sector, efficient and sustainable solutions are required.

Generally, incineration is a main way to manage municipal solid waste in Europe, particularly in France. Bottom ash is a granular solid obtained after the incineration of solid waste. This residue is an alternative material and strategic for construction available in large quantities (each year, more than 3 million of tons of bottom ash are produced in France [2,3,4]). Estimation about production of MSWI bottom ash in Europe is reported in Table 1. MSWI bottom ash is mainly consists of glasses, ferrous and non-ferrous particles, organic materials and mineral fraction [2].

Bottom ash is not considered as raw material, but it holds the status of waste and thus it is necessary to perform a specific characterization for identifying the compatibility criteria and technical barriers for using it as replacement of natural aggregates in concrete production. The quality of the mineral fraction used in civil construction depends on the efficiency of upstream sorting, on the incineration process, on the treatments technologies for recovering metallic particles and on the maturation step. However, before using it for the substitution of natural aggregate in building sector, current technologies are required to remove metallic particles, glasses and organic matter. In addition, the recovery of ferrous and non-ferrous metals is an essential step of the bottom ashes treatment process, both for the environmental advantage of metal scraps recycling and the reduction of the negative effects of metal [5].

The recycling of MSWI bottom ash such as by-products has been studied for decades in many areas as reported in Table 2 and proposals are still developed in several countries. Nevertheless, conventional dry technologies used in mostly of European countries are not efficient in recovering metallic particle from fine materials. In this experimental investigation, a specific treatment is developed for recovering ferrous and non-ferrous from fine materials (0-4 mm) and elaborate an upgraded sand fraction from MSWI bottom ash in order to avoid swelling phenomena that appears in the concrete applications [6,7,8]. The MSWI bottom ash was collected from a municipal solid waste incinerator in France.

Table 1: Amounts of bottom ash produced in Europe [9]

Country	Incinerated waste [million tons]	Bottom ash [million tons]
Belgium (2010)	3.03	0.51
Czech Republic (2010)	0.51	0.16
Denmark (2008)	3.59	0.63
Finland (2009)	0.27	0.05
France (2010)	14.1	3.0
Germany (2010)	20.04	5.00
Hungary (2008)	0.40	0.09
Italy (2010)	4.71	1.27
Netherlands (2011)	7.2	1.6
Norway (2010)	1.35	0.25
Portugal (2011)	1.13	0.21
Spain (2011)	2.42	0.42
Sweden (2009)	4.50	0.74

Table 2: Common reuse and recycle of MSWI bottom ash [9]

Country	Use as secondary construction material
Austria	No intention to reuse except as landfill structure material
Belgium	Use of granulates in road construction, concrete products
Denmark	Roads subbase and embankments, filler marine structures (dams, ports), construction material for parking and small building
France	80% of bottom ash recovered in road construction
Germany	Road subbase construction, recovery on landfills (roads, shaping) or storage in salt mines
Italy	Recovery in cement kilns, road construction, landfill construction
Netherlands	Roads subbase and embankments, noise barriers, foundation material, concrete products, landfill prohibited
Portugal	Road construction, recovery on landfill sites (as construction layers)
Spain	Road construction, recovery on landfill sites (as construction layers)
Sweden	Reuse as landfill covering material
UK	55% reused as road material in 2011

The aim of this study is to find a secondary construction material for the substitution of natural aggregates in concrete applications in order to preserve non-renewable natural resources and consequently reduce the carbon footprint of building sector. First of all, this paper focused on the characterization of upgraded mineral sand fraction (0-4 mm) from MSWI bottom ash and secondly the feasibility of concrete production with this upgraded sand as replacement of natural sand. The sand fraction (0-4 mm) was screened into two fractions: 0-2 mm and 2-4 mm. Physical characterization of upgraded mineral sand (grain size distribution, specific density, and water absorption), chemical and leaching tests have been performed on each fraction and the results have been compared with properties of natural sand usually used in France for concrete production. A preliminary test campaign carried out by utilizing 100% MSWI bottom ash 0-2 mm fraction for the substitution of natural sand in mortar applications at 14 days of curing.

2. Physical characterization

Physical characterization of materials is one parameter that could describe the mechanical behavior of products. According to XP18-545 French standards, there are 04 kinds of aggregates: A, B, C and D. Technical specifications that represent each category are reported in Table 3 [10].

Table 3. Technical specifications of sand fraction for mortar and concrete applications [10]

Code	A	B	C	D
Water absorption WA_{24} (%)	≤ 2.5	≤ 5	≤ 6	FTP[b]
Passing to 2 D[a] (%)	100	100	100	FTP[b]
Passing to 1.4 D[a] (%)	≥ 95	≥ 95	≥ 95	≥ 95
Passing to D[a] (%)	85 to 99	85 to 99	85 to 99	85 to 99
Fine content (%)	≤ 10	≤ 16	≤ 16	≤ 22
Methylene bleu content (MB)	≤ 1	≤ 2	≤ 2	FTP[b]

[a] Larger diameter of grain

[b] Product Data Sheet

In this experimental investigation, three kinds of natural sand have been identified for comparison to upgraded mineral sand fraction from MSWI bottom ash: CEN standardized sand according to EN 196.1 (CG_SN) and two fractions 0-2 mm and 2-4 mm of natural sand from quarry of Normandie in France (CG_Car_Vau-0-2 mm ; CG_Car_Vau_2-4 mm).

Natural sands usually used in concrete applications are classified in category A [10,11]. In addition, specific gravity of natural sand varies between 2.65 and 2.75t/m^3, with remarkably low water absorption [10].

MSWI bottom ashes were sampled according to EN 932-2 standards, the specific gravity was performed by pyknometer of helium and physical parameters are summarized in Table 4. Grain size distribution of bottom ash 0-2 and 2-4 mm and natural sand identified in this study are reported in Fig. 1. As it can be seen, grain size distribution of MSWI bottom ash 0-2 mm and 2-4 mm (CG_BA_0-2 mm and CG_BA_2-4 mm) have the same trend respectively of CG_SN sand, Car_Vau-0-2 mm and Car_Vau_2-4 mm sand. The specific gravity of bottom ash is similar to natural sand identified. Furthermore, it can be observed that water absorption content of upgraded bottom ash (W_{Ab} equal to 7.50%) is considerably higher than natural sand.

As it can be seen in the physical parameters (grain size distribution and specific gravity), MSWI bottom ash could be replace the granular skeleton of natural sand in concrete applications.

According to XP18-545 French standards, MSWI bottom ash 0-2 mm is classified to category D while MSWI bottom ash 2-4 mm is classified to category C.

Table 4. Physical parameters of sampled MSWI bottom ash

Test	Reference Method	Results Bottom ash 0-2 mm	Results Bottom ash 2-4 mm
Grain size distribution	EN 933-1	Well-graded	Uniform
Fine content	EN 933-1	6.2 %	3.2 %
Water absorption WA_{24}	EN 1097-6	7.50 %	5.40 %
Specific gravity	-	2.61 t/m^3	2.61 t/m^3
Apparent gravity	EN 1097-3	1.05 t/m^3	1.15 t/m^3

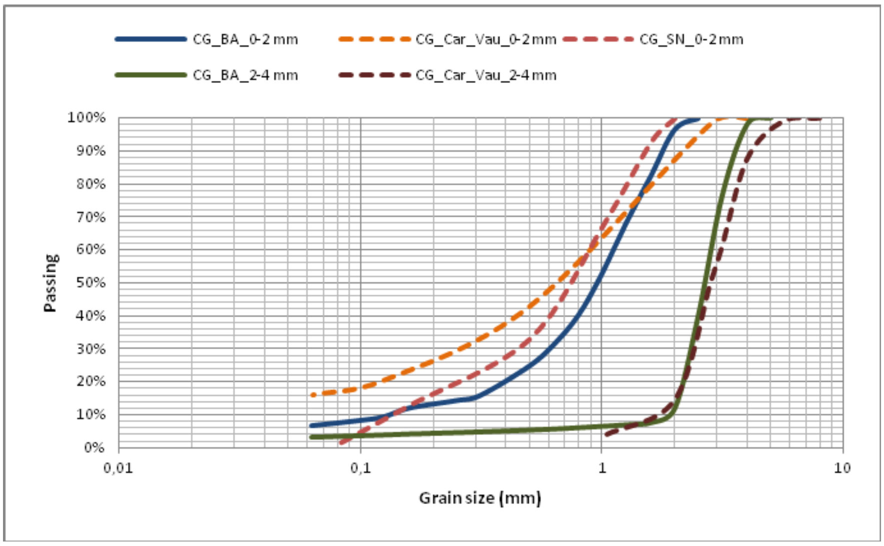

Fig. 1. Grain size distribution of utilized bottom ash. Continuous line: bottom ash fraction 0-2 and 2-4 mm.

Dashed line: natural sand 0-2 mm and 2-4 mm usually used in France.

3. Chemical characterization

3.1. Mineralogical composition of sampled MSWI bottom ash 0-2 mm

According to the literature review, chemical composition may vary according to the bedrocks. Generally natural sand is characterized by a high fraction of silicon dioxide (SiO_2), more than 95% in the CEN EN 196.1 standardized sand for example [11].

Informations on chemical and mineralogical composition of MSWI bottom ash have been obtained through X Ray Fluorescence (XRF) machine, of type S4 Pioneer from Bruker Axs. Results on mineralogical composition of MSWI bottom ash 0-2 mm fraction are reported in Table 5.

Table 5. Mineralogical composition of MSWI bottom ash 0-2 mm

Elementary composition	Wt (%)	Oxides	Wt (%)
Si	18.3	SiO_2	39.1
Ca	16.2	CaO	22.7
Al	4.4	Al_2O_3	8.3
Na	3.4	Na_2O	4.6
Fe	2.4	Fe_2O_3	3.4
S	1.3	SO_3	3.2
Mg	1.2	MgO	2.1
P	0.9	P_2O_5	2.1
Ti	0.4	TiO_2	0.7
Zn	0.4	ZnO	0.5

It can be observed that sampled MSWI bottom ash 0-2 mm is mainly consists of silicon dioxide, calcium oxide and aluminum oxide (~ 70%). Hematite Fe_2O, sodium oxide Na_2O and magnesium oxide are also identified in the sampled bottom ash. On the other hand, Rutile TiO_2 and ZnO have been found as minor crystal components (≤ 1%).

It can also be observed that the silicon oxide content in bottom ash 0-2 mm is lower than natural sand. However, according to the literature review [12], the presence of fine bottom ash might be slightly lead to pozzolanic properties which are responsible for the increasing of mechanical resistance. A further analysis is therefore necessary for confirming this point of view.

3.2. Environmental and health considerations

Leaching tests have been carried out on materials from solid wastes before reusing it in construction sector. The main threats to human health are heavy metals present in the bottom ash 0-2 mm like Cr, Cd, Cu, Mo, Ni, Pb, Sb, Se, Zn. In order to evaluate the leachability of these metals on the environment, leaching tests have been performed, following the experimental protocol NF EN 12457-2. The average results are reported in Table 6.

Table 6. Leaching tests of 0-2 mm MSWI bottom ash fraction

Parameter	Leaching values (mg/kg)	Threshold values set by French legislation (mg/kg)	Threshold values of non-hazardous waste set by EU legislation (mg/kg)
As	< 0.1	0.6	2
Ba	0.9	28 - 56	100
Cd	< 0.002	0.05	1
Cr	< 0.01	1 - 2	10
Cu	1.0	50	50
Hg	-	0.01	0.2
Mo	< 0.1	2.8 - 5.6	10
Ni	< 0.02	0.5	10
Pb	< 0.04	1 - 1.6	10
Sb	< 0.1	0.6 - 0.7	0.7
Se	< 0.1	0.1	0.5
Zn	< 0.02	50	50
pH	11.07	-	-
Soluble fraction	0.22%	20 000	-
Chloride	2940	5 000 - 10 000	15 000
Sulfate	7930	5 000 - 10 000	20 000
Fluor	~ 1	30 - 60	150

It can observed that the leaching values of MSWI bottom ash 0-2 mm are below the threshold values set in French Ministerial Decree of November 18^{th} 2011. Therefore, MSWI bottom ash can be reused in construction sector without risk of groundwater contamination. However, a further analysis has been performed on the bound material dependent on the planned application.

According to the European legislation of waste, MSWI bottom ash was categorized as non-hazardous waste because leaching values are lower than the threshold values.

4. Mortar applications and testing

4.1. Materials and methods

In order to investigate the potential use of upgraded MSWI bottom ash as a substitute for natural sand in concrete applications, a preliminary campaign has been carried out and two sets of mixing were prepared. In the first set, CEN standardized sand and cement were used with W/C ratio of 0.5 according to EN 196.1 standards. In the second set, natural sand was totally replace by MSWI bottom ash 0-2 mm (by volume) and a superplasticizer was used at 0%, 1.5%, 2% and 3% by weight of cement to reduce the water content of mixing. The cement used in this experimental investigation is blast furnace cement “CEMIII/A 42.5N”. Mix compositions are reported in Table 7. Samples sized 4 × 4 ×16 cm were moulded for each mix and totally immersed during time of curing. Compressive and flexural strengths were tested on samples after 14 days of curing with a 150kN mechanical press.

Table 7. Mix compositions

Sample label	SN	SM0%	SM1.5%	SM2%	SM3%
W_{eff}/C ratio	0.5	0.5	0.5	0.5	0.5
Cement mass (g)	450	450	450	450	450
Natural sand mass (g)	1350	0	0	0	0
Bottom ash mass (g)	0	950	950	950	950
Water mass (g)	225	296.3	290.9	289.1	285.5
Superplasticizer (g)	0	0	6.75	9	13.5

4.2. Results and discussion

Average compression and flexural strengths are summarized in Figure 2, showing data for 14 days curing time. Following observations can be outlined:

a) The replacement of natural sand by upgraded MSWI bottom ash without superplasticizer (SM0%) decreases considerably compressive strength and slightly flexural strength.
b) Considering the sampled MSWI bottom ash results, the compressive strength increase with the superplasticizer ratio, following a linear trend. The superplasticizer reduces water content of mixing and therefore decreases the porosity of samples, hence the increasing of compressive strength.
c) Flexural strength results of MSWI bottom ash are similar regardless of the superplasticizer content. The linear trend observed in the compressive strength is not similar in flexural strength.
d) The compressive strength of SM1.5% and SM2% are almost similar. Otherwise, adding 0.5% by weight of cement does not improve considerably the mechanical resistance. Nevertheless, it can be observed a rapid increase of resistance (~ 7 MPa) up to 3% of superplasticizer by weight of cement. Therefore, a further investigation must be carried to determine the environmental impact of an increased amount of superplasticizer used for the concrete containing bottom ashes [13].
e) After 14 days of curing and without superplasticizer, compressive strength of sampled MSWI bottom ash is about 20 MPa. Hence, it means that upgraded MSWI bottom ash could be used to substitute natural aggregates in concrete applications and should get a good mechanical resistance after 28 days of curing. On the other hand, the doubt remains on the swelling phenomena occurring in concrete by-products containing bottom ash. Therefore, the study developments are oriented towards the expansion and swelling phenomena.

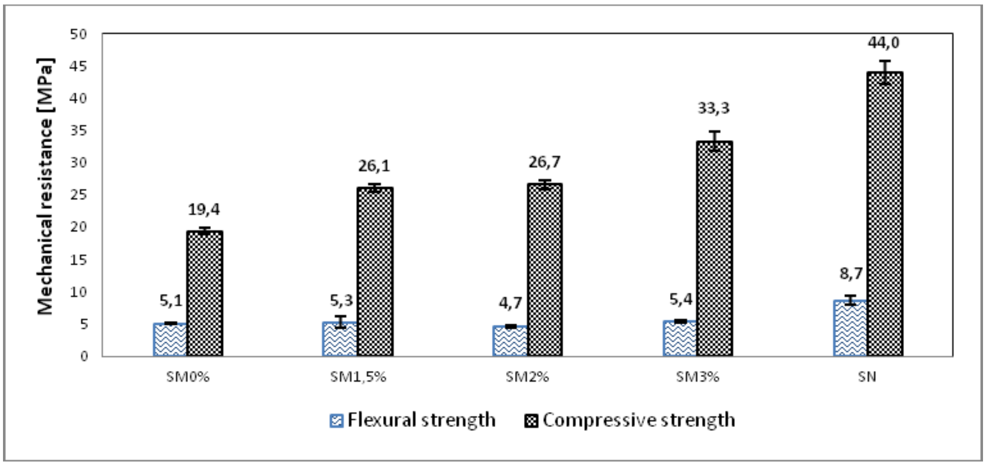

Fig. 2. Average results comparison for mechanical resistances of different mixes after 14 days of curing.

5. Conclusions and perspectives

This study focused on the characterization of upgraded MSWI bottom ash and the feasibility for the total substitution of natural aggregates in concrete applications in order to preserve non-renewable natural resources and reduce the carbon footprint of buildings sector.

The physical characterization showed upgraded mineral sand is a slightly heterogeneous material that presents the same properties as natural sand (specific density equal to 2.61 and grain size distribution). On the other hand, it can be observed that absorption content of upgraded bottom ash (W_{Ab} equal to 7.50%) is considerably higher than natural sand. Some mineral additions as superplasticizer could be used to reduce the water content of mixing and improve the workability.

Chemical characterization revealed that upgraded mineral sand bottom ash 0-2 mm is mainly consists of silicon dioxide, calcium oxide and aluminum oxide (~ 70%). Silicon dioxide content of bottom ash 0-2 mm (39.1%) is lower than natural sand (more than 95%) [11]. A further analysis is therefore necessary for determining a potential relationship between the silicon dioxide content in material and the increasing of mechanical resistance. Leaching tests have been performed on bottom ash 0-2 mm. The results showed that the leaching values are lower than the threshold values set in French Ministerial Decree of November 18th 2011. This upgraded sand was categorized as non-hazardous waste according to European legislation of wastes. Therefore, upgraded bottom ash 0-2 mm fraction can be reused in concrete application without risk of groundwater contamination.

A preliminary campaign of testing sampled MSWI bottom ash 0-2 mm for the total substitution of natural aggregates in concrete application have been performed at 0%, 1.5%, 2% and 3% of superplasticizer content. After 14 days of curing, compressive strength results were respectively 19.4 MPa, 26.1 MPa, 26.7 MPa and 33.3 MPa. It can be observed a linear trend in the compressive strength but not in the flexural strength. Regarding compressive strength, the results show that by increased ratio of additive the variability of material properties also increases. However, study developments are oriented towards the analysis of pozzolanic properties of fine bottom ash fraction.

The substitution of natural sand by upgraded mineral sand fraction from MSWI bottom ash is one solution to preserve non-renewable natural resources in the construction and therefore, reduce the carbon footprint of buildings sector. It can be observed through this experimental investigation the technical feasibility for the substitution of natural aggregate in concrete applications. However, further analyses are currently processing for determining thermal, physical and mechanical properties of concrete containing bottom ash and durability assessment.

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