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Low risk meat and bone meal (MBM) bottom ash in mortars as sand replacement

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Abstract

This paper presents the physical, chemical and mineralogical characteristics of meat and bone meal bottom ash (MBM-BA) from low-risk sources. It also gives a first evaluation, from a technical and an environmental point of view, of its potential of use as sand in cement-based materials. Results show that MBM-BA has the physical characteristics of a fine sand. It has low friability but high water absorption, which leads to a recommended use of less than 30% MBM-BA as sand replacement in mortars and the use of a superplasticizer. The compressive strength of mortar containing 17% of MBM-BA is similar to that of a reference mortar and the leaching behavior resembles that of the reference mortar without residue. These preliminary results lead us to believe that low-risk MBM-BA could be used in cement-based materials and present a promising way of reusing this residue.
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Keywords: Reuse; Meat and bone meal; Bottom ash; Characterization; Leaching

1. Introduction

Meat and bone meal (MBM) is a by-product of the food industry, obtained by the removal of fat (rendering) from mammal carcasses by a process of crushing, cooking and grinding. In Europe, more than 3 M tons of MBM are produced annually [1] (850 000 tons in France in 2002 [2]). Until 1994, most of the MBM produced in Europe was used as animal feed, fertilizer and in other industrial applications. However, since the transmissible spongiform encephalopathy (TSE) crisis, MBM has been progressively banned from animal feed:

- 1994: the Commission of the European Communities prohibited the feeding of protein derived from mammalian tissues to ruminant species [3] (in France, a decision was taken in 1990 restricting the feeding of mammal protein to cattle [4]).
- 1996: French decree on the prohibition of all feeding of animal proteins to ruminants [5].
- 2000: European Council Decision [6] on the suspension of feeding animal proteins to ruminants, pigs and poultry.

The consequence of these bans was a significant increase in the amount of MBM to be eliminated either by incineration or by other techniques. Incineration is one of the most commonly used methods to eliminate MBM, but it produces ash and bottom ash that must be managed.

The aim of this paper is to present the basic physical, chemical and mineralogical characteristics of meat and bone meal bottom ash (MBM-BA) from low-risk sources (MBM from healthy, non-infected animals intended for human consumption), and to provide a technical and environmental assessment of its potential for use as a substitute for sand in cement-based materials.

2. Background

Before May 1st 2003, MBM were classified in Europe [7] according to whether they came from sources defined as high risk or low risk. The high-risk source concerned principally the MBM obtained from animals infected by transmissible spongiform encephalopathy (TSE), animals that had died of

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Table 1
Chemical composition of cement (wt.%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI
20.1	5.6	2.0	62.5	3.1	0.2	0.9	3.2	1.7

natural or unknown causes, and specified risk materials (SRM) such as brains, eyes, tonsils and spinal cords of bovine, ovine and caprine animals [8]. The low-risk source included MBM from healthy, non-infected animals intended for human consumption. On May 1st 2003, the distinction between high- and low-risk MBM was replaced in Europe by a categorization of all animal by-products, including MBM [9].

– Category 1 (part of former high risk) includes by-products of animals suspected of being infected by TSE (transmissible spongiform encephalopathies) and specified risk materials (SRM).
– Category 2 (part of former high risk) includes by-products of animals presenting a risk of an infection other than TSE, animals that have died in ways other than being slaughtered and animals killed to eradicate an epizootic disease.
– Category 3 (former low risk) includes by-products arising from the production of goods intended for human consumption using slaughtered animals not affected by any signs of diseases communicable to humans or animals.

Since June 28th 1996 in France [10], all high-risk MBM are co-incinerated through specific channels, mainly in the cement industry, except for MBM coming from animals having TSE (special industrial waste incineration [11]). The cement kilns, where the temperature reaches 1450 °C, present good conditions for complete combustion in terms of temperature and time spent in the kiln [12] and should lead to the destruction of all organic matter, including proteins such as prions. In 2003, the cement industry incinerated 400 000 tons of MBM as alternative fuel in more than 20 cement plants in France (205 000 tons in 2000, 260 000 tons in 2001, 350 000 tons in 2002) [2,13].

Since late 2000 [14] in France and early 2001 [6] in the rest of Europe, low-risk MBM is no longer used in animal feeds. Other applications including MBM have been proposed, such as phenolic concrete blocks (without Portland cement), composed of 85% raw MBM and 15% phenolic resin acting as the cementing part [15]. According to its inventors, the material was 30% cheaper than traditional concrete and offered adequate modeling, strength and fire resistance properties. The project was not pursued further because of strong opposition by the French construction industry [16], which invoked possibly poor properties related to the durability of the blocks and their leaching behavior, during and after their normal life.

Since landfilling implies significant cost and loss of calorific potential, most low-risk MBM is now destroyed by incineration. In 2001, 3 640 000 tons of MBM, which included 1 346 000 tons of stored MBM [2], was intended for incineration in Europe. Incineration of MBM reduces the tonnage of material to be landfilled and also generates power, but it produces ash and bottom ash that must be managed. Considering the fraction of inorganic residue which remains from the combustion of MBM and taking the average of values (between 13% and 30%) found previously [17–19], incineration could lead to more than 1 M tons of ash per year having to be managed in Europe.

To the authors' knowledge, few papers have been published about MBM ash, and none of the results concern MBM bottom ash. McDonnell et al. [20] and Conesa et al. [12] studied the combustion behavior of MBM from a thermal point of view. Deydier et al. [18] evaluated the potential of MBM ash to entrap lead from water effluent. Only the British Research Establishment (BRE) [21] performed a short feasibility study of the use of MBM fine ash in concrete, without evaluating the pollution potential of the material.

3. Materials and experimental methods

3.1. Characterization of MBM-BA

Low risk meat and bone meal (from pork production), sometimes including small amounts of other wastes as co-combustion materials (plastic bags, sewage sludge), were incinerated at high temperature (1000 °C). The sample used in this study, obtained from three batches between 2002 and 2004, is representative of the production of MBM-BA for this site. The detailed characteristics of MBM-BA, which are given in Section 4, should not be generalized to other MBM-BA without performing supplementary tests.

The measurement of the physical properties included evaluation of the particle size distribution by sieving and the specific surface area by the one-point BET method (nitrogen adsorption), using a Micromeritic Automate 23 Desorb 2300A. A friability coefficient, based on French standard P18-576 [22] was measured using a micro-Deval apparatus. This coefficient, related to the attrition resistance of the materials, was obtained by measuring the fraction of fines

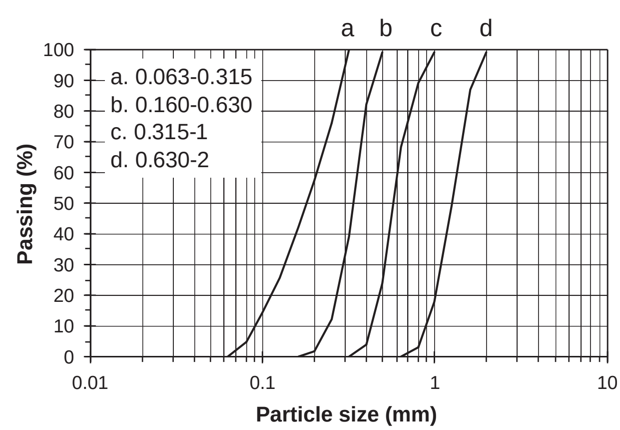

Fig. 1. Particle size distribution of quartz sands.

Table 2
Mortar mix details

	Partial replacement				Total replacement	
	Ref_1 (0%)	17%	33%	50%	Ref_2 (0%)	100%
Grading of sand	NF EN 196-1 (Fig. 4)				Particle size distribution of MBM-BA	
MBM-BA (g)	0	230	446	675	0	1350
Sand (total, g)	1350	1120	904	675	1350	0
Sand (grading)						
0.063–0.315 (%)	27	22	17	11	24	0
0.160–0.630 (%)	–	–	–	–	28	0
0.315–1 (%)	31	21	11	0	38	0
0.630–2 (%)	42	40	39	39	10	0
Cement (g)	450	450	450	450	450	450
Water (g)	225	225	225	225	383	383
Water absorbed by MBM-BA (g)	0	25	49	74	0	149
Free water (g)	225	200	176	151	383	234
w/c (total)	0.50	0.50	0.50	0.50	0.85	0.85
w/c (effective)	0.50	0.44	0.39	0.34	0.85	0.52
Super plasticizer (% dry)	–	0.1 (SP 1)	0.4 (SP1)	0.8 (SP1)	–	0.4 (SP1) 1.0 (SP2)

under 0.1 mm produced by the grinding of the whole material (2–4 mm in P18-576) in a rotating standard cylinder. The water absorption coefficient was measured according to European Standard EN 1097-6 [23]. The coefficient is defined as the mass of water absorbed in open pores of dry-surface saturated aggregate over the dry mass of the material.

The elemental composition was measured by inductively coupled plasma–atomic emission spectrometry (ICP–AES) for major oxides, and by inductively coupled plasma–mass spectrometry (ICP–MS) for minor elements.

Mineralogical properties were obtained by X-ray powder diffractometry using a Siemens D5000 diffractometer operating with Co Kα radiation ($\lambda = 1.789$ Å). Measurements were made with a 2θ step interval of 0.02° (5°–70°) and an acquisition time of 12 s per step.

3.2. Tests on mortars containing MBM-BA

The binder was a standard CEM I 52.5 (Table 1) as specified in European Standard EN 197-1 [24], with a specific area (Blaine) of 400 m^2/kg. The aggregates used were four quartz sands of different grading (Fig. 1). De-ionized water was used for all experiments. Two commercial superplasticizers (SP1 and SP2) were used.

The mortar mixtures (Table 2) were designed and prepared according to French standard NF EN 196-1 [25]. They were composed of three parts of sand and one part of cement (by mass). Replacement rates of sand were 17%, 33%, 50% and 100%. For the reference mortar (Ref_1) and mortars containing up to 50% of MBM-BA, the grading of sand was within the limits of the sand used in standard mortar tests (Fig. 4). A second reference mortar (Ref_2) was tested: its sand had the grading of MBM-BA in order to compare the results with mortars containing 100% MBM-BA. The water/cement ratios were fixed at 0.50 (partial replacement of sand) and 0.85 (total replacement of sand). Table 2 also gives the free water in the mortar mixtures (difference between total water and water absorbed by MBM-BA).

The mixtures were cast in 4 × 4 × 16 cm molds and sealed in plastic bags in a temperature controlled room at 20 °C. Strength tests were carried out at three hydration times (1, 3 and 28 days) and each value was the average of 6 tests.

The environmental study was performed using leaching tests (liquid–solid extractions) in order to evaluate the

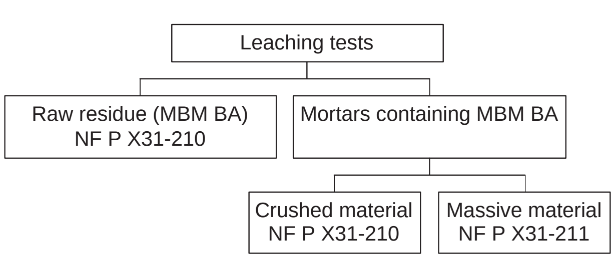

Fig. 2. Program of the leaching tests on MBM-BA.

Fig. 3. Meat and bone meal bottom ash (MBM-BA).

Table 3
Physical properties of MBM bottom ash

Density	2900 kg/m^3
Bulk density	900 kg/m^3
Specific surface area BET	3000 m^2/kg
Calculated	3 m^2/kg
Particle size distribution	0–2 mm
Mean diameter (d_{50})	0.4 mm
Morphology	Irregular particles
Absorption coefficient (water)	11%
Friability coefficient	37%

maximum quantity of pollutant released by the raw residue and by cement-based materials containing this residue. The test program is given in Fig. 2.

The leaching test on raw residue was performed according to French standard NF P X31-210 [26] (recently adopted as EN 12457-2) [27], developed for granular materials. In the case of mortars, two tests were carried out at 28 days of age: NF P X31-211 on monolithic material [28] and NF P X31-210 on crushed material. The former aims to assess the release from intact products, while the latter concerns the product after its destruction. Both tests were chosen in order to compare the results and to take account of:

– the potential of cement-based materials to retain pollutants in their hydrates and structure during their normal life (monolithic materials);
– the destruction of the structure at the end of their life, leading to the reuse or landfill of the old concrete containing the residue (granular materials).

The test on monolithic material was carried out on $3 \times 3 \times 8$ cm pieces, obtained from the sawing of the $4 \times 4 \times 16$ cm initial prisms. The test on granular material was carried out either on raw residue, or on mortar fragments finer than 4 mm, obtained from the crushing of $3 \times 3 \times 8$ cm mortar pieces.

All the tests consisted of three leaching cycles of 16 h in stirred de-ionized water with 8 h between cycles, when the leaching was stopped. New water was used for each leaching cycle. The liquid/solid ratio was set at 10. Measurements on the leachates collected after filtration (0.45 m) at 16 h, 32 h and 48 h, included pH and minor-element content (Ti, V, Cr, Ni, Cu, Zn, As, Cd, Sb, Ba, Pb) using ICP–MS.

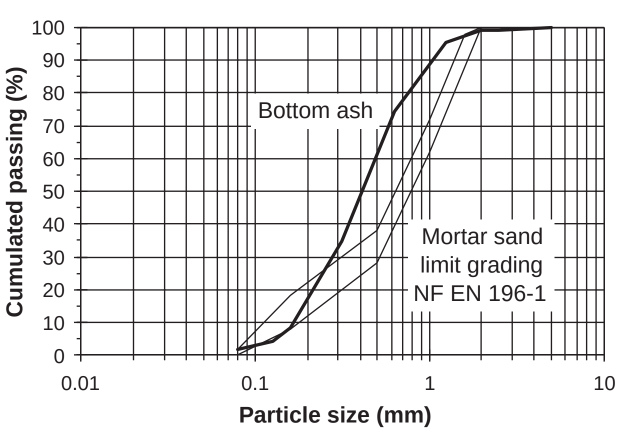

Fig. 4. Particle size distribution of MBM-BA, in comparison with the limits for sand used for standard mortar tests.

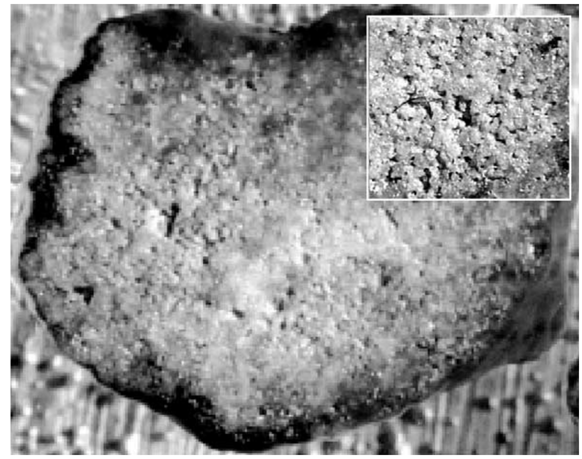

Fig. 5. Internal texture of an MBM-BA grain (optical microscopy on polished surface).

4. Characteristics of MBM bottom ash

MBM-BA has the physical aspect of a fine sand (Fig. 3 and Table 3), with a grading between 0 and 2 mm and a mean diameter of 0.4 mm. Fig. 4 gives its particle size distribution in comparison with the limits for the sand used in standard mortar tests [25].

The bulk density of MBM-BA is around 900 kg/m^3, much lower than that of the sand commonly used in cement-based materials (1500 kg/m^3). The average density of the particles is 2900 kg/m^3. The external specific area, calculated from the density and the particle size distribution (considering cylindrical particles), is about 3 m^2/g.

Optical and electronic microscopy show that MBM-BA is composed of irregular particles (Fig. 3). Many grains present a porous texture, as shown in Fig. 5. The BET method gives a specific area of 3000 m^2/kg, which is a thousand times higher than the value calculated using the particle size distribution. This significant difference is related to a large open porosity of the grains, leading to a water absorption of 11%, a very high value compared to normalized siliceous sand (less than 1% [29]).

The mechanical properties of MBM-BA were evaluated using a friability coefficient, defined as the fraction of the mass of crushed particles (less than 0.1 mm) relative to the mass of the whole material before crushing. The friability coefficient must be under 40% for 60 MPa concrete intended

Table 4
Chemical composition of MBM-BA (wt.%)

CaO	P_2O_5	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	MnO	Na_2O	K_2O	SO_3	Cl^-	LOI
50.45	39.85	1.34	0.33	0.22	1.24	<0.01	<0.03	1.59	0.29	0.41	0.38	1.18

Table 5
Trace elements in MBM BA (mg/kg)

As	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Dy
<0.50	43.18	<0.90	<0.05	<0.30	1.21	1.17	32.42	<0.20	70.31	0.07
Er	Eu	Ga	Gd	Ge	Hf	Ho	In	La	Lu	Mo
0.04	0.02	0.74	0.08	<0.08	0.12	0.014	<0.10	0.61	0.007	2.66
Nb	Nd	Ni	Pb	Pr	Rb	Sb	Sm	Sn	Sr	Ta
0.37	0.50	17.73	1.30	0.14	1.66	4.12	0.09	0.89	144.90	0.02
Tb	Th	Tm	U	V	W	Y	Yb	Zn	Zr	
0.01	0.21	<0.01	0.17	3.08	0.69	0.38	0.044	39.17	4.80	

for building construction. In the case of MBM-BA, the measured value of 37% suggests that the particles are resistant enough to be used as sand in cement-based materials.

The chemical composition of MBM-BA is given in Table 4 (major elements) and Table 5 (minor elements). The X-ray diffraction pattern is given on Fig. 6. These results show that MBM-BA is mainly composed of calcium phosphates: hydroxylapatite $Ca_5(PO_4)_3(OH)$ and whitlockite $Ca_3(PO_4)_2$. Calcium hydroxylapatite is the major inorganic constituent of bones and teeth. XRD measurements on selected particles (not presented here) also showed the presence of trace minerals such as quartz, hematite and magnetite, which probably came from other wastes used as co-combustion materials.

Trace element analysis (Table 5) showed a low pollutant content (<375 mg/kg), compared to many other waste materials such municipal solid waste incineration (MSWI) fly ash (>46 000 mg/kg) [30]. Only Sr, Cu, Ba, Zn, Cr and Ni were over 15 mg/kg.

The leaching behavior of MBM-BA is presented in Table 6, which gives the quantities of elements leached from MBM-BA for the three cycles of the test, compared to the initial content of harmful elements in MBM-BA. It can be seen that the leachate quantities are quite low compared to the total amount of elements in the raw bottom ash. The dissolved fractions (DF) are generally below 1%, except for V (1.7%), Sb (2.7%) and Pb (1.1%).

Table 6 also gives the threshold values, according to French regulation [31], allowed for leachates from municipal solid waste incineration (MSWI) bottom ash to be reused in road construction in France. This regulation divides MSWI bottom ash into three categories: weak leaching fraction (V), reusable in road construction; intermediate bottom ash (M), which can be treated (maturation) or landfilled; and strong leaching fraction (S), which must be landfilled. The comparison of the leached values with these thresholds shows that MBM-BA can be classified as a "weak leaching fraction" bottom ash. Thus, according to French regulation [31], MBM-BA could be allowed in road construction.

The difference of leaching of heavy metals (Fig. 7) shows that the use of total content of elements is not an adequate characteristic for the evaluation of the hazardous potential of a residue, since some elements are retained in the waste structure. A high heavy metal content in the whole material does not necessary mean that all pollutants will be released when the waste is leached. The lack of correlation between leachability and total concentration of elements has already been reported by van der Sloot [32].

5. MBM-BA in mortars as sand replacement

5.1. Preliminary study: raw MBM in mortars

Raw MBM is a fibrous material containing organic and mineral matter. It has a brownish color and an intense odor. Preliminary investigations were performed in 2001 [19] to evaluate the use of raw MBM in cement-based materials. Mortars were made, according to French standard NF EN 196-1, with 10% of raw MBM in mass replacement of cement and in mass addition (sand replacement) to cement. After a curing period of 28 days in water, compressive strength tests (Fig. 8) were performed on six 4 × 4 × 8 cm prisms for each mixture.

Compared to the reference mortar, mixtures with raw MBM showed significant losses of strength: strengths were 43% and 36% lower than reference mortar when 10% of raw MBM replaced cement and sand, respectively. These losses are certainly related to the organic matter contained in raw MBM. Consequently, the use of raw MBM in cement-based materials was judged unsatisfactory from a technical point of view. Similar dissatisfaction was voiced about the risks associated with the leaching behavior of organic matter including proteins such as prions.

5.2. The effect of MBM-BA on technological properties of mortars

Tests on mortars were carried out in order to evaluate the effect of MBM-BA on the consistency and compressive strength of cement-based materials. Increasing proportions of MBM-BA (17%, 33%, 50% and 100%) were used as replacement of siliceous sand in mortars.

The first trials rapidly showed a loss of workability of mortars (fluidity measurement under mortar vibration, also

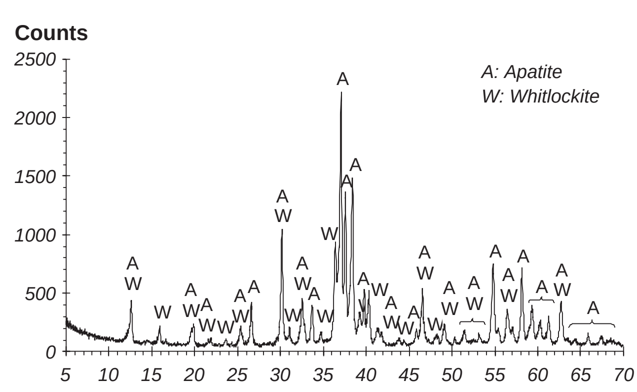

Fig. 6. XRD pattern of MBM-BA.

Table 6
Concentrations of leached elements of MBM-BA compared to total content and regulation thresholds for the use of MSWI BA in roadworks

	MBM-BA (total content)	Leached MBM-BA					Threshold MSWI BA [31]		
		Cycle 1	Cycle 2	Cycle 3	Total	DF	*V*	*M*	*S*
Ti (μg/kg)	<100 000	45	4.5	3.1	53	0.5%			
V (μg/kg)	3080	5.5	31	15	52	1.7%			
Cr (μg/kg)	32 420	278	6.6	26	310	1.0%	1500	3000	>3000
Ni (μg/kg)	17 730	1.0	2.4	3.9	7.3	0.04%			
Cu (μg/kg)	70 310	27	20	19	66	0.09%			
Zn (μg/kg)	39 170	100	106	41	247	0.6%			
As (μg/kg)	<500	1.8	0.1	0.1	2.0	0.4%	2000	4000	>4000
Cd (μg/kg)	<300	1.2	0.9	0.3	2.4	0.8%	1000	2000	>2000
Sb (μg/kg)	4120	57	27	29	113	2.7%			
Ba (μg/kg)	43 180	187	110	92	389	0.9%			
Pb (μg/kg)	1300	5.7	2.1	6.6	14.4	1.1%	10 000	50 000	>50 000
SO_4^{2-} (g/kg)	4				≤4		10	15	>15
SF	–				0.7%		5%	10%	>10%
LOI	1.2%	–	–	–	–	–	5%	5%	>5%

DF = dissolved fraction; *V* = weak leaching fraction, reusable in road construction; *M* = intermediate bottom ash, which can be treated (maturation) or landfilled; *S* = strong leaching fraction, which must be landfilled; SF = measured soluble fraction; LOI = loss on ignition.

known as LCL apparatus [33]) and a high water consumption due to the high absorption of MBM-BA. Hence, in order to maintain a correct consistency, it was decided to use a superplasticizer (SP1). In the case of partial replacements, the water cement ratio was kept at 0.50 (a value usually used to test mortars), but the amount of SP1 needed increased with the replacement rate of sand by MBM-BA: 0.1% (17%), 0.4% (33%) and 0.8% (50%). However, the replacement of the whole quantity of sand by MBM-BA necessitated a significant increase in the water content of the mixtures (w/c ratio of 0.85) and the use of 0.4% of SP1. Unfortunately it was found, after the mixing of this mortar, that SP1 acted as an air entraining agent and it was noticed that this mixture presented a foamy texture, with a density of 1.88 g/cm^3. So it was decided to test two other 100% MBM-BA mortars: one without admixture and another with a new superplasticizer (SP2), used at 1%.

Fig. 9 gives the compressive strength results at 1, 3 and 28 days for mortars containing up to 50% of MBM-BA in replacement of siliceous sand. The ratio of strengths between MBM-BA and reference mortars (0% MBM-BA) are illustrated on Fig. 10. For short hydration times (1 and 3 days), the use of 17% MBM-BA led to a significant increase in compressive strength, while the other mixtures (33 and 50%) presented similar strengths compared to the reference mortar. At 28 days, the strength was similar for 17% MBM-BA, but lower when the amount of ash increased. The good short-term results could be due to the presence in MBM-BA of Cl^-, which is known to be a strength accelerator. Table 7 shows that the amounts of chlorides in the mortars, calculated from the quantity of Cl^- in MBM-BA (0.38%), are in the range of the quantities used for commercial accelerators. However, Cl^- limits the increase of strength for long hydration times, probably explaining why the strengths are not maintained over time. Moreover, it is also recognized that Cl^- has an important role in the corrosion of steel, which would preclude the use of raw MBM-BA in reinforced concrete.

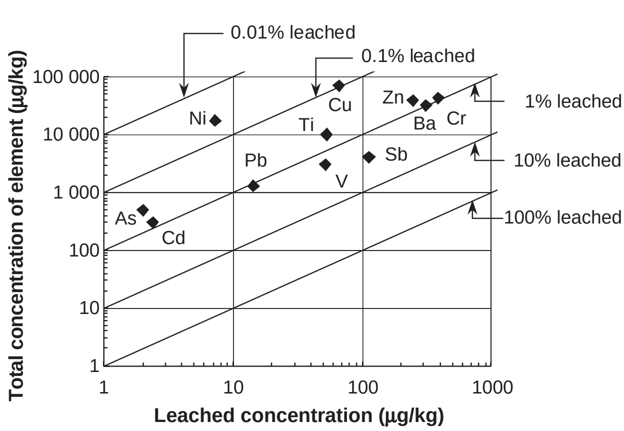

Fig. 7. Total concentration of minor elements in MBM-BA versus leached concentration.

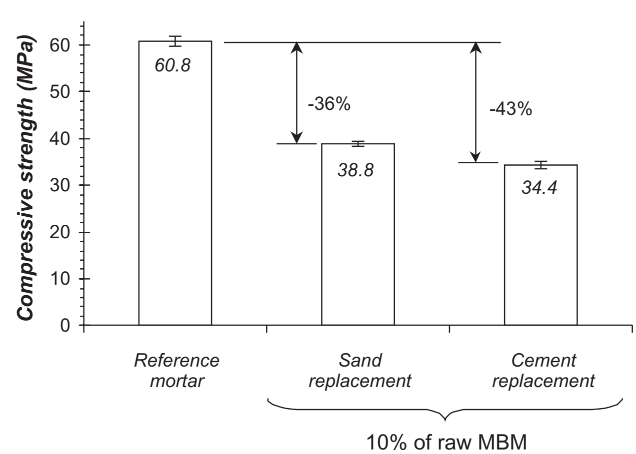

Fig. 8. Compressive strength (28 days) of mortars containing 10% of raw MBM (based on cement mass) in replacement of cement and addition to cement, compared to reference without raw MBM.

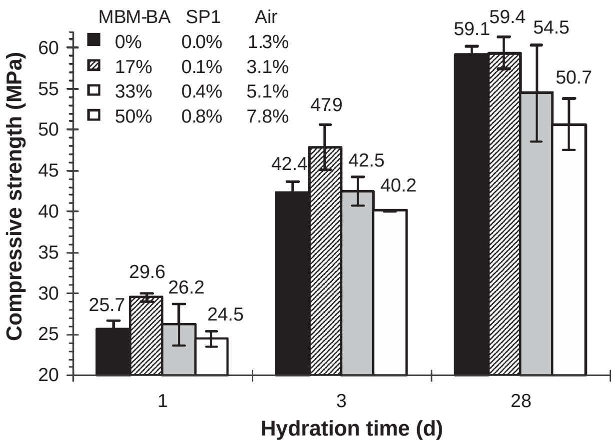

Fig. 9. Compressive strength at 1, 3 and 28 days of mortars containing 0%, 17%, 33% and 50% of MBM-BA in replacement of siliceous sand. SP1 was used in mortars with MBM-BA: 0.1% (17%), 0.4% (33%), 0.8% (50%).

The apparent increase (or small reduction) in strength which accompanies the introduction of MBM-BA is largely due to the absorption of a proportion of the mix water resulting in a reduced free water to cement ratio.

Fig. 11 presents the compressive strength at 28 days, the density and the air content of mortars containing 100% MBM-BA in comparison with a reference mortar (w/c = 0.85) without residue. The air content was calculated using the density of each constituent and the measured density of the fresh mortar. In the case of mortars with SP1, the compressive strength decreased to near the one third of the reference one. This low value is related to its foam texture. Mortar without SP also exhibited a significant loss of compressive strength (−76%), due to a high proportion of air voids and a low density. In this case, the mortar, which presented the texture of a shotcrete, was too dry to settle properly in the mould. Only mortar with SP2 gave good results since the compressive strength was very similar to the reference. However, the water content must be increased and

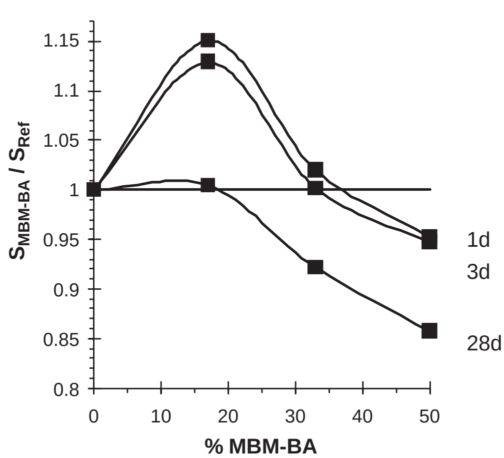

Fig. 10. Ratio of strength at 1, 3 and 28 days of mortars containing 17%, 33% and 50% of MBM-BA in replacement of siliceous sand, compared to reference mortar (0% MBM-BA).

Table 7
Chlorides in mortars due to the presence of Cl^- in MBM-BA

Chlorides in MBM-BA mortars	17% MBM-BA	33% MBM-BA	50% MBM-BA
Cl^- in kg per m^3 of mortar	0.96	1.85	2.75
Cl^- in % compared to the mass of cement	0.19	0.37	0.57

a superplasticizer must be used in order to maintain sufficient workability.

Although it seems conceivable to use MBM-BA to replace the whole quantity of siliceous sand in mortars, the water and superplasticizer demand would probably remain too high to ensure adequate long term performance, especially from a durability point of view.

In order to get free of the effect of air content, measured strengths were compared to the strength (S) calculated using Bolomey's Law (Eq. (1)).

$$S = B\left(\frac{c}{w+a} - 0.5\right) \quad (1)$$

where c and w are the masses of cement and free water in the mixture, respectively, a is the volume of air, and B is a parameter which takes into account the characteristics of the cement and aggregate used. In our case, B was calculated using the reference mortar containing only siliceous sand.

The results, reported in Table 8, show that the measured compressive strengths were lower than the predicted strength, meaning that MBM-BA has lower mechanical properties compared to siliceous sand.

In short, from a technological point of view and when considering mixtures containing the same amount of water (and

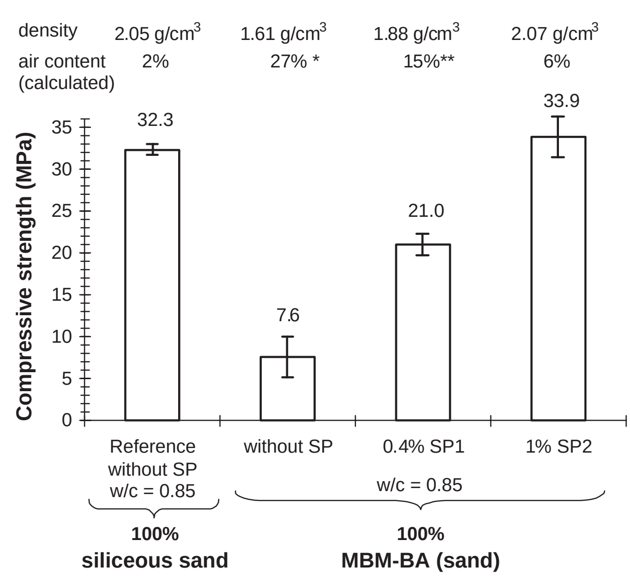

Fig. 11. Compressive strength (28 days), density and air content of mortars containing 100% of MBM-BA in replacement of siliceous sand, compared to reference without MBM-BA. *Texture of a shotcrete; **SP1 acted as an air entraining agent.

Table 8
Density, air content and 28-day compressive strength (predicted and measured) of mortars containing 17%, 33%, 50% and 100% of MBM-BA in replacement of siliceous sand

	17% MBM-BA	33% MBM-BA	50% MBM-BA	100% MBM-BA		
				SP1	SP2	without SP
Density of fresh mortars (g/cm^3)	2.24	2.21	2.17	1.88	2.07	1.61
Air content (calculated, in %)	3.1	5.1	7.8	15	6.2	27
Calculated compressive strength (MPa)	62.1	63.9	63.6	25.5	42.1	10.6
Measured compressive strength (MPa)	59.4	54.5	50.7	21.0	33.9	7.6
Variation of strength due to MBM-BA (%)	−4.4	−15	−20	−18	−19	−28

neglecting the absorption of MBM-BA), the results of this preliminary study showed that:

– 17% of the siliceous sand could be replaced by MBM-BA in mortars, since the compressive strengths were always higher than or equal to reference.
– 33% and 50% replacement led to correct results in the short term (similar to reference) but the strength decreased at 28 days.
– 100% replacement could lead to strength equivalent to the reference, but the water content would have to be significantly increased in order to maintain correct workability.
– In all cases, the use of a compatible superplasticizer with MBM-BA should minimize the loss of strength but the increase of cost is unfavorable to high replacement rates.
– The air content of the mortar containing MBM-BA should be controlled.

It would probably have been more realistic to test the MBM-BA in a saturated surface dry condition. Pre-saturation of the MBM-BA would have reduced the quantity of superplasticizer required to achieve a plastic mortar thus improving the economics of utilization. However, the strengths would have been reduced as a function of the higher free w/c.

Finally, it must be kept in mind that strength is only one characteristic of importance with regard to the performance of an aggregate in concrete and other aspects of performance should be taken into account before any use at a larger scale.

5.3. Effect of MBM-BA on environmental properties of mortars

The results of the leaching tests are given in Table 9 for monolithic mortars and in Table 10 for crushed mortars. Concentrations are expressed in µg per kg of solid leached.

For both monolithic and crushed mortars, no general tendency can be observed for the kinetics of leaching during the three successive cycles since the leachates sometimes increased, sometimes decreased and sometimes remained constant over the leaching time.

The analysis of leaching results is divided into three parts: the first life of cement-based material (monolithic state), the destruction of the material (from monolithic to crushed state) and, finally, the second life of the material (crushed state).

5.3.1. Cement-based materials during their first life

The environmental impact of waste in cement-based materials during their service life is evaluated using monolithic materials. Thus, tests on massive mortars could indicate the potential of the overall material to retain pollutants in its structure during its normal life.

It can be seen from Table 9 that the environmental behavior of MBM-BA mortar with SP1 was the least good of all, since the total amount of minor elements leached was

Table 9
Concentrations of leached elements in monolithic mortars

	Reference mortar				100% MBM-BA mortar (SP1)				100% MBM-BA mortar (SP2)			
	Cycle 1	Cycle 2	Cycle 3	Total	Cycle 1	Cycle 2	Cycle 3	Total	Cycle 1	Cycle 2	Cycle 3	Total
Ti (µg/kg)	15	7.2	8.6	31	5.2	20	8.5	34	7.7	35	7.3	50
V (µg/kg)	9.6	7.0	0.7	17	13	3.4	0.6	17	9.1	3.8	9.0	22
Cr (µg/kg)	99	21	17	137	43	28	18	89	27	11	16	54
Ni (µg/kg)	64	7.4	3.1	74	10	4.7	2.8	18	9.2	11	10	30
Cu (µg/kg)	30	21	11	62	38	93	18	149	26	30	20	76
Zn (µg/kg)	147	46	211	404	73	105	118	296	58	142	161	361
As (µg/kg)	0.5	0.3	0.9	1.7	1.1	1.7	1.1	4.0	0.3	1.0	1.1	2.4
Cd (µg/kg)	7.3	1.6	0.3	9.2	10.2	1.1	0.7	12.0	1.9	0.9	0.4	3.2
Sb (µg/kg)	0.8	1.8	0.4	3.0	3.0	0.6	0.4	4.0	2.3	0.4	0.6	3.3
Ba (µg/kg)	388	408	214	1010	804	434	273	1511	498	29	169	696
Pb (µg/kg)	8.9	4.3	4.3	17	68	5.0	2.9	76	5.2	6.6	4.3	16
Total (µg/kg)	770	529	471	1767	1069	697	444	2209	645	271	399	1314
pH	12.3	11.7	11.6		12.2	11.8	11.8		12.2	11.9	11.8	

Table 10
Concentrations of leached elements in crushed mortars

	Reference mortar				100% MBM-BA mortar (SP1)				100% MBM-BA mortar (SP2)			
	Cycle 1	Cycle 2	Cycle 3	Total	Cycle 1	Cycle 2	Cycle 3	Total	Cycle 1	Cycle 2	Cycle 3	Total
Ti (μg/kg)	291	190	352	833	89	81	54	224	104	66	110	280
V (μg/kg)	56	27	205	288	5.1	14	101	120	8.6	7.3	11	27
Cr (μg/kg)	460	87	284	831	321	46	431	798	344	350	433	1127
Ni (μg/kg)	82	103	114	299	49	72	131	252	39	47	54	140
Cu (μg/kg)	1538	408	204	2150	234	217	191	642	303	222	312	837
Zn (μg/kg)	1721	1829	821	4371	4421	2417	663	7501	998	1834	1159	3991
As (μg/kg)	31	14	20	65	8.2	11	20	39	11	16	16	43
Cd (μg/kg)	17	11	4.9	33	7.2	3.7	4.0	15	7.4	4.1	9.1	21
Sb (μg/kg)	8.7	7.3	21	37	6.5	4.5	16	27	7.1	4.5	5.4	17
Ba (μg/kg)	7054	561	3508	11 123	5881	356	2385	8622	7123	3860	2988	13 971
Pb (μg/kg)	81	81	52	214	52	51	73	176	60	53	123	236
Total (μg/kg)	11 340	3318	5586	20 244	11 074	3273	4069	18 416	9005	6464	5221	20 690
pH	12.8	12.8	12.7		12.7	12.8	12.6		12.7	12.7	12.8	

higher than for the two other mortars. Concerning heavy metals, only 3 elements (Cr, Ni, Zn) were less leached than in the reference mortar, while 7 elements were in higher concentrations in the leachate. Among these, As, Cu, Pb had a leached concentration more than twice the reference one. This poor performance could be related to the highly porous structure of this mortar (Fig. 11), which would be unable to retain heavy metals.

Globally, MBM-BA mortar with SP2 presents adequate environmental behavior, since the total amount of minor elements leached was lower than from other mortars. It released smaller amounts of heavy metals than the reference mortar for 6 elements out of 11 (Cd, Cr, Ni, Zn, Ba and Pb). Ti, V, Sb, Cu and As were leached in higher concentrations, but always less than 50% over the values for the reference mortar. This behavior could be related to the structure of MBM-BA mortar, which is less porous than the reference mortar (as a result of the lower cement paste free water/cement ratio) and has similar mechanical properties (Fig. 11

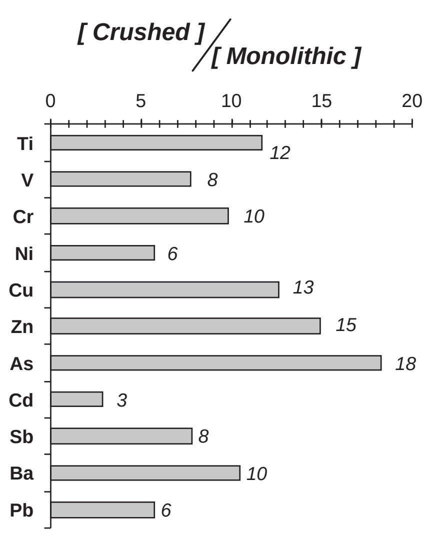

Fig. 12. Ratio of leached concentrations between crushed and monolithic mortars for each element (combined results of all three mortars).

— Rc 100%). Moreover, a positive effect of MBM-BA cannot be excluded.

These results highlight the significant effect of porous media structure in the leaching of elements. The release of elements is limited due to transport constraints and the slow diffusion of the ions in the cement matrix. They also show that it is preferable to avoid cement-based materials presenting insufficient performance when using waste in the mixture.

5.3.2. From monolithic state to crushed state

At the end of their normal life, cement-based products are destroyed, either to be landfilled or to be reused in new construction materials. The environmental behavior of construction debris in new bound applications such as concrete could be assessed from the monolithic state. This is not the case for the leaching behavior of debris to be used or disposed in an unbound form, for which tests should be carried out on granular materials.

As was seen in Tables 9 and 10 presenting the results for both monolithic and granular form, the size reduction process significantly modified the leaching behavior of mortars. As expected, the increase of surface contact due to mortar grinding led to higher concentrations of leachates. For the three mortars leached, the total amount of minor elements leached was 8 to 16 times higher for crushed mortars. The harmful effect related to the destruction of the material is also illustrated in Fig. 12, which presents the ratio of leached concentrations between crushed and monolithic mortars for the eleven minor elements analyzed (combined results of all three mortars). The leachates of crushed mortars had heavy metal concentrations up to 18 times those obtained for monolithic mortars. The size reduction process strongly affected elements such as As, Zn, Cu and Ti, while it had less significant effect on Cd, Ni and Pb.

5.3.3. Cement-based materials during their second life

The test on crushed mortar is normally used to evaluate the retention properties of the matrix and it could be interpreted as the potential of the cement to trap or integrate

Table 11
Leaching behavior of raw MBM-BA and crushed mortars compared to European waste acceptance criteria in landfill [34,35]

	Waste acceptance criteria [34,35]			Crushed mortars			
	Inert (i)	Non-hazardous (nh)	Hazardous (h)	MBM-BA	Ref	SP1	SP2
Ti (μg/kg)		Not specified		53	833	224	280
V (μg/kg)		Not specified		52	288	120	27
Cr (μg/kg)	500	10 000	70 000	310 i	831 nh	798 nh	1127 nh
Ni (μg/kg)	400	10 000	40 000	7 i	299 i	252 i	140 i
Cu (μg/kg)	2000	50 000	100 000	65 i	2150 nh	642 i	837 i
Zn (μg/kg)	4000	50 000	200 000	247 i	4371 nh	7501 nh	3991 i
As (μg/kg)	500	2000	25 000	2.0 i	65 i	39 i	43 i
Cd (μg/kg)	40	1000	5000	2.4 i	33 i	15 i	21 i
Sb (μg/kg)	60	700	5000	113 nh	37 i	27 i	17 i
Ba (μg/kg)	20 000	100 000	300 000	389 i	11 123 i	8622 i	13 971 i
Pb (μg/kg)	500	10 000	50 000	14 i	214 i	176 i	236 i

the heavy metals in its hydrates. So, this test could be related to the destruction of the structure at the end of its life, leading to the reuse or landfill of the old concrete containing the residue.

In order to study the possibility of disposal in landfill, results can be compared to the thresholds given in European regulations [34,35] concerning the classification of waste to be landfilled. Table 11 categorizes raw MBM-BA and the three crushed mortars according to the amount of element leached in regard to European waste acceptance criteria for landfills of waste. Except for antimony (Sb), raw MBM-BA can be considered as inert waste. In the case of crushed mortars, more elements are released than for raw MBM-BA. Chromium (Cr), copper (Cu) and zinc (Zn) release lead to a classification of the mortar as non-hazardous (nh) waste. However, it must be noted that the leached concentrations are much closer to those of inert materials than to the non-hazardous threshold. Concerning the effect of MBM-BA, mortars with residue are not more harmful, regarding leaching behavior, than reference mortar.

The comparison of the results between monolithic and crushed states for SP1 mortars shows the difference in the phenomena involved in the retention of elements in a cement-based material: the hydrates of cement can trap heavy metals (Table 10) even if the mortar is too porous to retain the elements adequately (Table 9).

Finally, it can be seen from Table 10 that the leaching behavior of the three mortars is comparable. These results could mean that cement traps and includes some of the minor elements in its hydrates, as already stated by other authors [36–44]. Moreover, it cannot be discarded that MBM-BA could also absorbs heavy metals in its structure. This effect could be expected since MBM-BA is mainly composed of apatites, minerals recognized for their retention properties with respect to elements [45–53]. However, this assumption must be demonstrated by direct methods.

6. Conclusion

Since the TSB crisis, Europe has had to increase its capacity to eliminate MBM and incineration has been a major method adopted by many countries. The incineration produces ash that must be managed. This paper presented a characterization of MBM-BA and the preliminary tests for its possible use as sand in cement-based materials. It must be noticed that the results presented here concerned one sample of bottom ash from meat and bone meal. Other tests should be performed with other ashes before any generalization of the conclusions.

The results for this MBM-BA showed that:

– MBM-BA had the physical and mechanical characteristics of a sand, but it had high water absorption, which led to the use of a superplasticizer and limited the sand replacement to less than 30%.
– the compressive strengths of a plasticized EN 196-1 test mortar containing 17% of MBM-BA were similar to those of the reference mortar.
– the leaching tests on MBM-BA in mortars gave results similar to those for the reference mortar without residue. It could be presumed that MBM-BA absorbed heavy metals in its structure. However, this assumption must be demonstrated by direct methods.

Regarding these preliminary results, the reuse of MBM-BA from the incineration of low-risk MBM in cement-based materials is conceivable and could present a promising way to eliminate this residue. Other technological and environmental tests should be performed, including field scale experiments.

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