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Characteristics of industrial and laboratory meat and bone meal ashes and their potential applications

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Abstract

This paper reports the characterization of four meat and bone meal (MBM) ashes obtained from specific incineration (laboratory) and from co-incineration (industrial process). Three out of the four MBM ashes were mainly composed of calcium phosphates (hydroxyapatite and whitlockite). Their compositions (major and trace) were in the range for natural phosphate rocks. Trace element contents, including heavy metals, were below 0.6% and industrial ashes contained much more heavy metals than laboratory ash. The amounts of leached elements were low, especially for laboratory ash. According to the European classification of waste to be landfilled, the laboratory ash can be classified as an inert waste. Two industrial ashes are mostly inert. Only one ash is highly leachable and needs a stabilization treatment to be classified at least in the category of hazardous waste. It seems, from these results, that possibilities other than landfilling could be considered to give economic value to these ashes.
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Keywords: Meat and bone meal ash; Bottom ash; Fly ash; Calcium phosphate; Hydroxyapatite; Whitlockite; Chemical properties; Chemical composition; Heavy metals; Leaching

1. Introduction

Meat and bone meal (MBM) is a by-product of the rendering industry. The total production of MBM for the European Union (EU) exceeds 3,500,000 tons/year, including more than 700,000 tons in France [1]. In Europe, since May 1, 2003, MBM has been classified with other animal by-products according to whether they come from sources defined as categories 1, 2 or 3 [2].

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

The progressive restriction of the use of MBM (including category 3) in applications, such as animal feed [7–10] (except pet food [2,11]) has led to a significant increase in the amount of MBM to be eliminated. Since June 28, 1996 in France [3], MBM from categories 1 and 2 are co-incinerated through specific channels, mainly in the cement industry. Only MBM coming from animals having TSE are subjected to special industrial incineration [4]. Cement kilns, where the temperature reaches 1450 °C, provide good conditions for complete combustion in terms of temperature and time spent in the kiln [5] 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 and 350,000 tons in 2002) [1,6].

Considering that MBM has a heating value ranging between 13 and 30 MJ/kg [5,12–22], incineration in a thermal plant could be one of the most appropriate methods to eliminate this residue. Several studies available on the thermal behavior of

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MBM confirm this interest. These studies include specific incineration [5,15,16,18,22,23], co-combustion [12–14,18–25] and pyrolysis [5,15,17,22] of MBM. However, it should be kept in mind that incineration always produces ashes that must then be managed. It has been shown that between 100 and 310 kg of ash is produced for each ton of MBM that is incinerated [5,12–19,22,23,26,27]. Thermal treatment of the entire production of MBM in Europe would then produce a large amount of ash (350,000–1,000,000 tons/year). Therefore, the fate of such a stock of ashes is a major environmental concern.

The aim of this paper is to present and compare the chemical, mineralogical, physical and leaching characteristics of meat and bone meal ashes (MBM category 3) obtained from one laboratory and one industrial process, in order to classify these wastes and evaluate possible ways of valorization. This paper reports one of the first exhaustive characterizations of industrial MBM ashes, since almost all other studies found in literature concerned ashes obtained on a laboratory scale.

2. Materials and methods

The experimental methods used for the physical and chemical characterization of the ashes are summarized in Table 1. The measurement of the physical properties included the density by hydrostatic weighting, the particle size analysis (sieving for MBM-BA and laser diffraction analyzer for other ashes) and the specific surface area (Blaine apparatus, NF EN 196-6). Electron scanning microscopy (SEM) observations was performed to study the morphology of ashes with JEOL JSM-6380 LV, coupled with EDX analysis. The chemical composition, carried on lithium tetraborate/lithium metaborate flux obtained at 1100 °C, was realized using atomic adsorption with flame atomization (Fe, Na, K, Ca, Mg, Si) and inductively coupled plasma coupled with mass spectrometry (ICP-MS: P, heavy metal and lanthanide). Loss on ignition was measured by calcinations at 1000 °C. Mineralogical properties were obtained by X-ray powder diffractometry using a Siemens D5000 diffractometer equipped with a monochromator and using a Kα ($\lambda = 1.789$ Å) cobalt anticathode. Measurements were made with a 2θ step interval of 0.02° (5° to 70°) and an acquisition time of 10 s/step. Water absorption coefficient of MBM-BA was realized according to standard EN 1097-6. 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 evaluation of environmental impact was performed with the European standard EN 12-457. The liquid:solid ratio was 10:1, the extraction medium was demineralised water and the extraction time was 24 h. Measurements on the leachates collected after filtration (0.45 μm) included major (Ca, Si, Fe, Na, K, Mg) and trace (Ti, V, Cr, Ni, Cu, Zn, As, Cd, Sb, Ba, Pb) element contents using atomic adsorption and ICP-MS, respectively.

Three kinds of ashes were studied, two from an industrial combustion process and one incinerated at laboratory scale. The industrial ashes were bottom ash (MBM-BA) and fly ash (MBM-FA) coming from an incineration plant equipped with an industrial rotary furnace (12 m long). This incinerator has a capacity of 2 tons/h and the maximum temperature reached near the flame is 1000 °C. The incinerator was fed with 95% of meat and bone meal from pork production (category 3), the remaining 5% being composed of other waste, such as plastic bags or sewage sludge. The remaining amount of residue ranged between 10 and 15% by mass of MBM. Two batches of ashes were used and mixed together in order to take into account of the variability of industrial production.

Flue gases (45,000 N m^3/h) were treated with sodium bicarbonate at the incineration plant before their recovery. Stream treatment produced a significant amount of soluble salts, reaching almost 50% by mass of the total MBM fly ash (MBM-FA). So it was decided to study the crude ash and its washed part separately. MBM-FA was washed with deionized water for 20 min

Table 1
Experimental methods for the physical and chemical characterization of MBM ashes

Property	Test method/standard
Density	Hydrostatic weighting
Particle size distribution	Sieving (MBM-BA), laser granulometry in ethanol (MBM-FA and MBM-LA)
Specific surface area	Blaine (NF EN 196-6)
Morphology	Secondary electron microscopy (SEM—JEOL JSM-6380 LV), coupled with elemental analysis (EDX)
Water absorption coefficient	Ratio of the mass of water absorbed in open pores of dry-surface saturated aggregate to the dry mass of the material (NF EN 1097-6)
Chemical analysis	
Tetraborate metaborate lithium flux at 1100 °C	
- Fe, Na, K, Ca, Mg, Si	Atomic absorption with flame atomization
- P, heavy metal and lanthanide	Inductively coupled plasma-mass spectrometry (ICP-MS)
Other techniques	
- Chlorides	Potentiometric titration with silver nitrate
- Sulphates	Gravimetric analysis
Mineralogy	X-ray diffraction (XRD), Siemens D5000, Co Kα radiation ($\lambda = 1.789$ Å) 2θ step interval of 0.02° (5° to 70°) and acquisition time of 10 s
Leaching behavior	European Standard EN 12457-2, ratio of liquid:solid, 10:1; extraction medium, demineralised water; one extraction time of 24 h

Table 2
Chemical compositions of MBM-BA, crude and washed MBM-FA and MBM-LA (wt.%)

	Ca	P	Si	Al	Mg	Fe	Na	K	SO_4^{2-}	Cl^-	LOI
MBM-BA	28.8	16.2	3.7	1.1	1.2	1.5	2.7	1.7	0.8	0.3	0.3
MBM-FA (crude)	12.7	7.8	1.5	tr	0.5	0.5	15.5	8.1	16.6	11.2	8.6
MBM-FA (washed)	24.6	15.4	3.6	0.9	1.3	1.4	4.4	2.5	1.7	0.7	5.8
MBM-LA	28.2	18.9	0.7	tr	0.7	0.1	2.4	1.5	0.4	2.0	3.6

LOI: loss on ignition; tr: trace.

in a stirred container, using a water:ash ratio of 20. The filtered residue was then dried at 40 °C. The filtrate was evaporated and analysis of the residual solid showed that it contained essentially Na^+, K^+, SO_4^{2-}, Cl^- and some heavy metals (total of 430 mg/kg, mostly Zn—350 mg/kg). Salts could be recovered for industrial applications, as is done for wastewater from the washing of municipal solid waste incineration (MSWI) fly ash [28–30].

The properties of the industrial ashes were compared to those of a laboratory ash (MBM-LA). MBM-LA was the incineration residue of meat and bone meal from slaughterhouse waste, combusted in a laboratory electric furnace at 850 °C in air atmosphere. The incineration process was operated in two steps: an initial combustion of 3 h at 600 °C to eliminate the organic fraction of the material, and a second combustion from 25 to 850 °C at a rate of 2 °C/min. During combustion, MBM particles melted and stuck together, inducing pyrolysis of organic matter trap inside. The first combustion gave a black residue (carbon-rich). This residue was mixed manually before a second combustion in order to complete decomposition and obtain clear ashes. Amount of residue represent nearly 24% weight of initial MBM.

3. Results and discussion

3.1. Chemical and mineralogical properties

The chemical compositions of MBM-BA, crude and washed MBM-FA and MBM-LA are given in Table 2 (major elements) and Table 3 (trace elements). Due to the high combustion temperature, the MBM ashes were composed of mineral matter.

3.1.1. Major elements

Industrial ashes (MBM-BA and washed MBM-FA) and laboratory ash (MBM-LA) had high calcium and phosphorus contents (Table 2), up to 47% of the total ash quantity. These results were expected, since the major non-organic fraction of MBM is bone, the mineral part of which is composed of calcium phosphates (mainly hydroxyapatite). MBM-LA had the highest Ca and P contents (47%), probably due to the absence of impurities in the specific incineration process. The lower contents for the industrial ashes may be explained by the fact that up to 5% of other wastes were incinerated with MBM in the industrial incineration plant. Other elements (Si, Al, Mg, Fe, Na, K, SO_3^{2-} and

Table 3
Trace elements in MBM-BA, crude and washed MBM-FA and MBM-LA (mg/kg)

	Ba	Bi	Cd	Ce	Co	Cr	Cs	Cu	Dy	Er
MBM-BA	208.4	0.5	0.3	10.0	9.5	136.2	1.5	189.5	0.7	0.4
MBM-FA (crude)	158.0	0.5	1.7	4.9	73.5	115.3	1.5	133.2	0.3	0.2
MBM-FA (washed)	184.6	0.5	0.4	9.5	24.3	155.3	2.0	213.7	0.6	0.4
MBM-LA	120.7	$<4.10^{-3}$	0.3	0.8	3.7	20.8	1.1	46.6	0.1	5.10^{-2}
	Ga	Gd	Ge	Hf	Ho	La	Lu	Nb	Nd	Ni
MBM-BA	3.5	0.7	<3.3	0.1	0.2	17.8	0.1	1.7	4.2	93.0
MBM-FA (crude)	3.7	0.3	<3.3	0.0	0.1	9.5	0.0	2.9	1.7	97.0
MBM-FA (washed)	6.3	0.6	<3.3	0.1	0.1	16.5	0.1	2.7	4.0	119.9
MBM-LA	1.9	0.1	0.1	$<8 \times 10^{-3}$	0.0	25.5	0.0	1.6	0.3	78.4
	Pb	Pr	Rb	Sb	Sc	Sm	Sn	Sr	Ta	Tb
MBM-BA	<19.3	1.0	13.7	8.7	25.6	0.9	10.1	273.8	$<1 \times 10^{-3}$	0.1
MBM-FA (crude)	<19.3	0.4	93.3	12.1	26.9	$<4.10^{-2}$	22.8	104.1	$<1 \times 10^{-3}$	3.10^{-2}
MBM-FA (washed)	<19.3	1.0	29.9	36.9	31.5	0.7	48.3	237.0	$<1 \times 10^{-3}$	0.1
MBM-LA	<19.3	0.1	13.1	4.6	17.8	1.10^{-2}	1.5	172.1	1.10^{-2}	6.10^{-3}
	Th	Ti	Tl	Tm	U	V	Y	Yb	Zn	Zr
MBM-BA	1.0	725.4	0.1	4.10^{-2}	1.2	206.1	4.7	0.4	262.0	2.8
MBM-FA (crude)	0.7	385.9	5×10^{-2}	$<4 \times 10^{-3}$	0.4	177.6	1.8	0.2	1349.0	2.5
MBM-FA (washed)	1.1	842.2	0.1	4.10^{-2}	1.1	197.3	4.1	0.4	3372.8	2.6
MBM-LA	0.6	64.3	8×10^{-3}	0.1	0.2	11.8	0.4	0.1	373.1	1.6

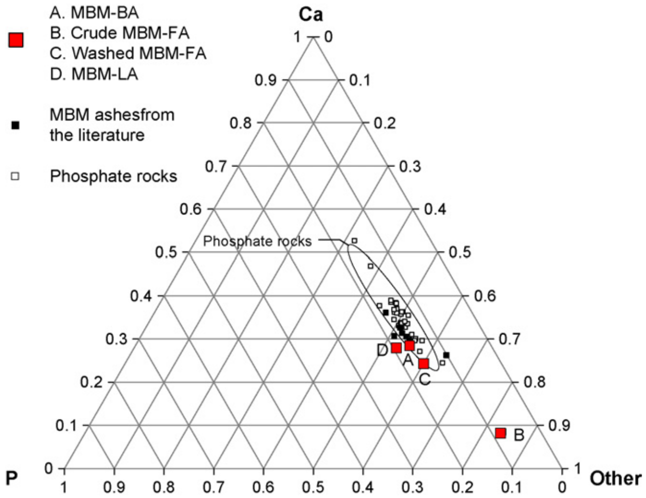

Fig. 1. Ternary diagram of MBM ash and phosphate rock compositions [12–14,20,21,27,31–36].

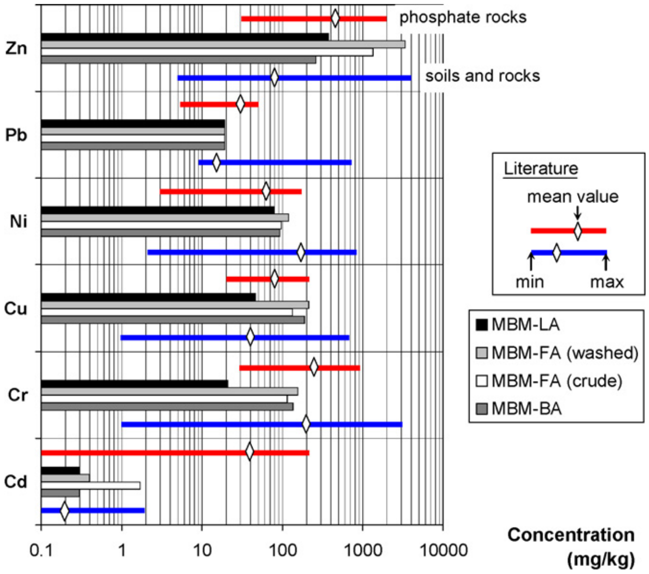

Fig. 2. Heavy metal contents of MBM ashes compared to natural phosphate rocks [32–36] and typical soils and rocks [39–49].

Cl^-) made up 8% of MBM-LA, 13% of MBM-BA and 16% of washed MBM-FA.

Only crude MBM-FA had a notably different composition from other ashes, since it contained a significantly high amount of sulfates, chlorides and alkalis (Na and K). These elements are present as soluble salts in water and they represented almost 50% by mass of the total ash.

Fig. 1 gives a ternary representation of the chemical compositions of the four MBM ashes, compared with the compositions of other MBM ashes found in the literature [12–14,20,21,27,31]. Except for the crude MBM-FA, it can be seen that the ashes from this study had similar compositions with other MBM ashes from different origins. It is interesting to note that the calcium and phosphorus contents in MBM ashes (25–29% Ca and 15–19% P) were of the same order of magnitude with the average contents found by other authors [32–36] in natural phosphate rocks (35 ± 2% Ca and 15 ± 1% P).

3.1.2. *Trace elements*

Table 3 gives the trace element contents of MBM ashes. The total amounts made up less than 0.6% in all cases, since they reached 2200, 2800, 5500 and 960 mg/kg for MBM-BA, crude MBM-FA, washed MBM-FA and MBM-LA, respectively. Zinc was the main trace element of MBM-FA (0.1–0.3%) and MBM-LA (<0.1%), whereas Ti was the main one of MBM-BA (<0.1%). As expected, trace element analysis showed that meat and bone meal incinerated with other wastes (industrial ashes) contained much more hazardous element, mainly heavy metal, than meat and bone meal obtained from specific incineration (laboratory ash). In the case of industrial ashes (MBM-BA and MBM-FA), most trace elements and especially heavy metals, were present in higher concentrations in fly ash. Moreover, washed MBM-FA contained more trace elements than crude MBM-FA, indicating that heavy metals were mainly present as insoluble species.

A comparison of these results with those of literature [31–49] showed that MBM ashes from this study:

- contained more trace elements than other MBM ashes found in literature, especially for industrial ashes. For instance, the hazardous element content of MBM bottom ash studied by Cyr and Ludmann [31] was nearly 375 mg/kg. This difference could be related to the amount of other waste incinerated with meat and bone meal.
- Had much lower hazardous element contents than other incinerated wastes, such as municipal solid waste incineration fly ash (MSWI-FA) or sewage sludge ash (SSA), which contain more than 46,000 mg/kg [37] and 16,000 mg/kg [38], respectively.
- Had heavy metal concentrations of the same order of magnitude as those found in natural phosphate rocks [32–36] or typical natural soils and rocks [39–49] (Fig. 2).

3.1.3. *Mineralogical composition*

The mineralogical characteristics of the four MBM ashes are given in Fig. 3. As stated earlier, crude MBM-FA has a different composition compared to other ashes, due to the presence of a significant amount of soluble salts. Industrial ashes (MBM-BA and washed MBM-FA) are mainly composed of whitlockite (βTCP) $Ca_3(PO_4)_2$ and hydroxyapatite $Ca_5(PO_4)_3(OH)$, while laboratory ash (MBM-LA) contains only hydroxyapatite. Fig. 3 gives the main different peaks between these two minerals. These results are in accordance with the chemical compositions (Table 2) reported earlier, since calcium phosphates are the main components of these ashes. However, Ca/P molar ratios (1.38, 1.24 and 1.16 for MBM-BA, washed MBM-FA and MBM-LA, respectively) are lower than the values for hydroxyapatite (1.67) and whitlockite (1.5). These lower ratios could be due to either the presence of calcium-deficient apatite, as observed by Deydier et al. [27] in their IR structural analysis of MBM ashes, and/or the existence of other compounds containing phosphorus.

Moreover, it was observed that MBM-BA was a blend of white, brown and black grains. XRD analysis of these white

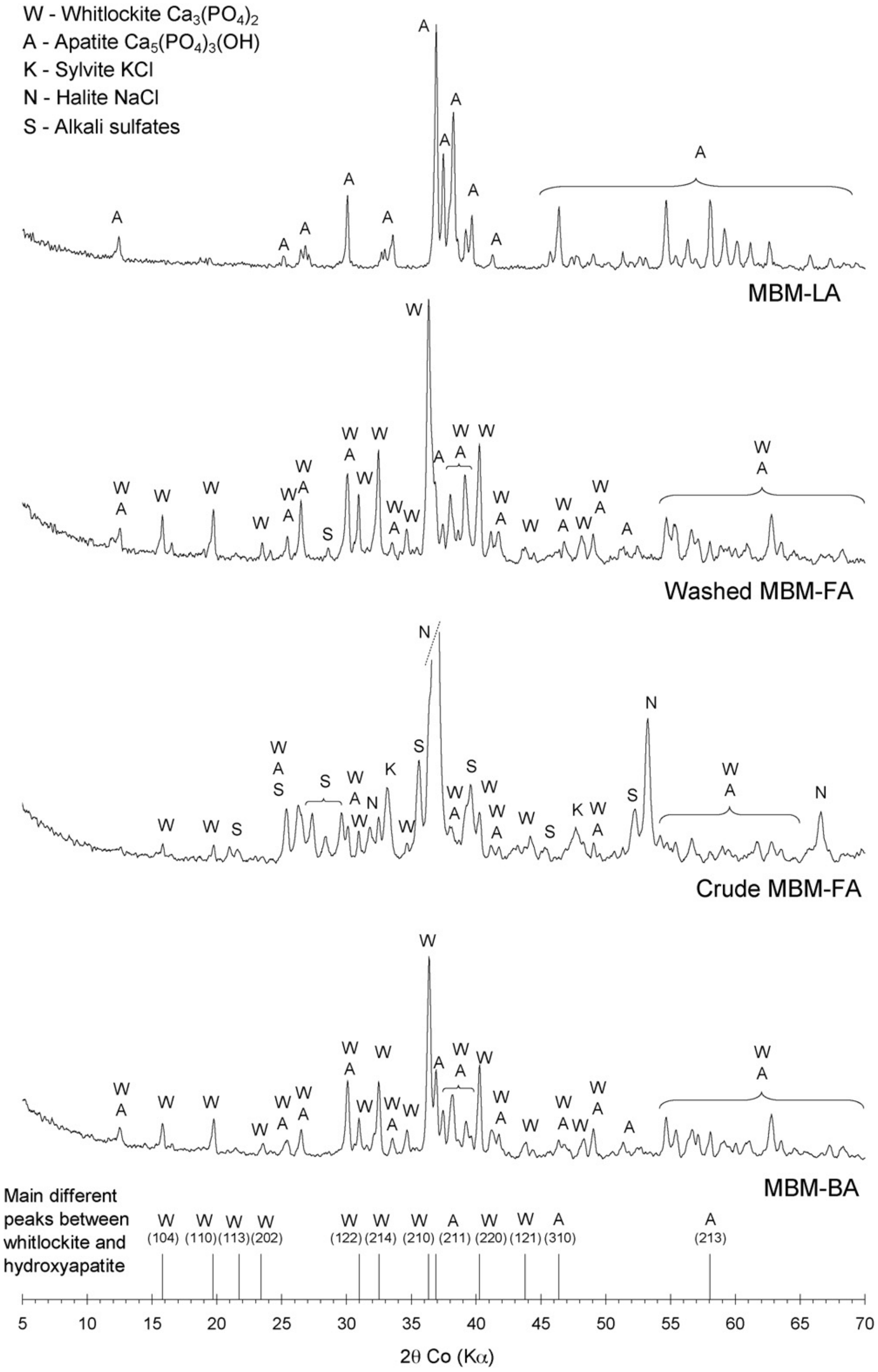

Fig. 3. XRD pattern of MBM-BA, crude and washed MBM-FA and MBM-LA.

and black grains showed they contained essentially hydroxyapatite and whitlockite, respectively (Fig. 4). The brown grains were mixtures of these two minerals, with an XRD pattern similar to that of the bottom ash as a whole (Fig. 3). This composition is similar to the one given by Cyr and Ludmann [31], who worked on MBM-BA from the same incineration plant. Only the proportions of minerals were different, thus confirming the variability inherent in any waste material.

The difference of mineralogical composition between these ashes could be explained by the presence of other waste material in the industrial ashes, and/or by the various incineration

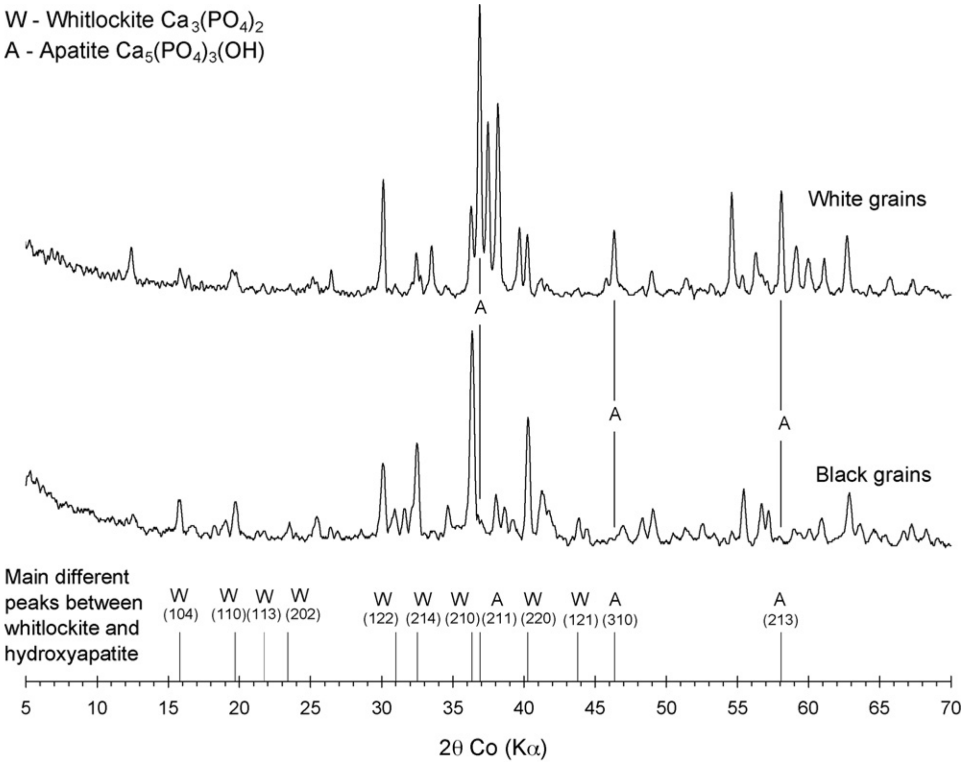

Fig. 4. XRD patterns of white and black grains from MBM-BA.

processes used as well as the various operating temperatures of incineration. Many authors [50–54] have reported the production of whitlockite/apatite mixtures from the heating of non-stoichiometric hydroxyapatite above 800 °C. This was confirmed on our products with a sample of MBM-LA (which did not contain whitlockite after laboratory incineration at 850 °C) combusted at 1100 °C for 1 h. Fig. 5, which compares the XRD patterns of MBM-LA incinerated at 850 and 1100 °C, shows the

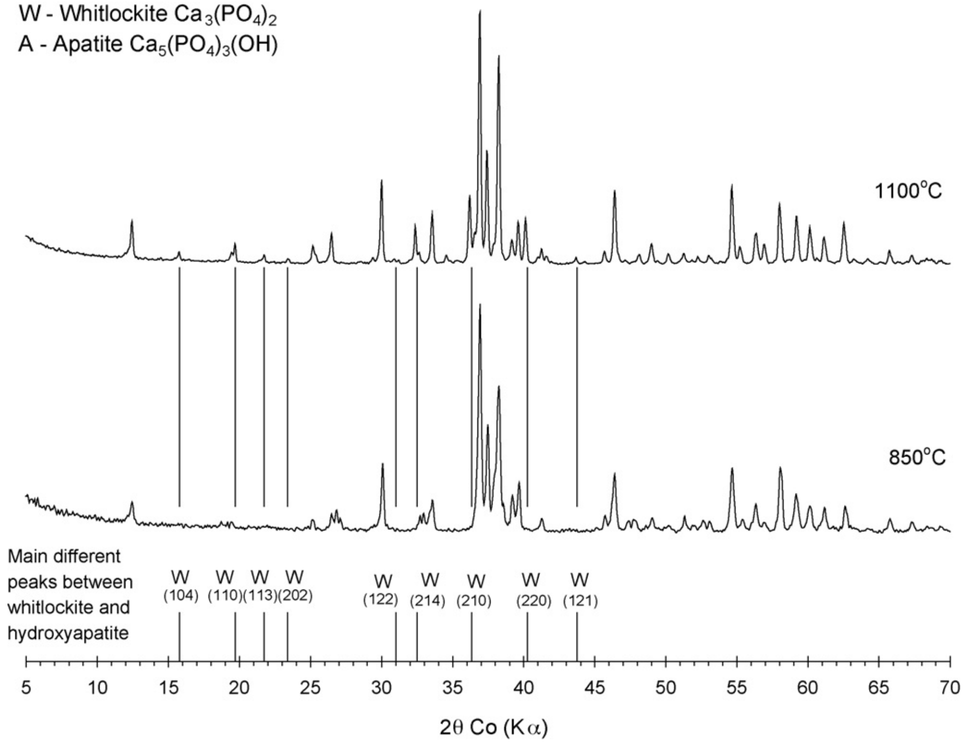

Fig. 5. XRD patterns of MBM-LA incinerated at 850 and 1100 °C.

Table 4
Physical properties of MBM-BA, crude and washed MBM-FA and MBM-LA

Ashes	D_{50} (μm)	Density (kg/m^3)	Color	Specific surface area blaine (m^2/kg)
MBM-BA	580	2940	White, black and brown	–
Crude MBM-FA	20	2610	White	800
Washed MBM-FA	70	2880	Light brown	110
MBM-LA	300	3040	Light brown	290

Fig. 6. Industrial meat and bone meal bottom ash (MBM-BA).

appearance of whitlockite peaks for the ash combusted at the higher temperature.

3.2. Physical properties

Meat and bone meal bottom ash (MBM-BA) has the same size as sand particles (Fig. 6), ranging from 0.04 to 4 mm, with a mean diameter (D_{50}) of 0.58 mm (Table 4). Its particle size distribution, measured by sieving, is given in Fig. 7. Some rare grains having a large diameter (over 30 mm) were intentionally removed. As seen on the SEM observations (Fig. 8), MBM-BA particles are mostly heterogeneous, porous and have an irregular form. The large open porosity of the ash leads to a water absorption coefficient (EN 1097-6) of 9%, which is high compared to the value for siliceous or calcareous sands (<1%).

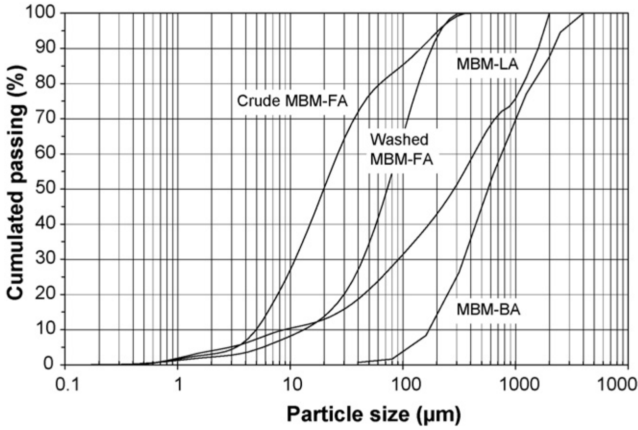

Fig. 7. Particle size distribution of industrial ashes (MBM-BA and MBM-FA) and laboratory ash (MBM-LA).

Crude and washed fly ashes (MBM-FA) are significantly finer than bottom ash, since their particle sizes range between 1 and 200 μm (Fig. 7), with mean diameters of 20 and 70 μm, respectively (Table 4).

The coarser particles of washed MBM-FA are probably due to the agglomeration of grains during the drying process. This agglomeration may also explain the large decrease in the Blaine specific surface area: 8000 and 1100 cm^2/g for crude and washed MBM-FA, respectively (Table 4).

Fig. 9 shows the morphology of MBM-FA. As for MBM-BA, washed MBM-FA is composed of heterogeneous grains having an irregular shape. Only a few particles show a spherical form. SEM observations of crude and washed MBM-FA (Fig. 9) brought out a similar morphology, except for the grain surfaces, which had thin deposits mostly, composed of S, Cl, K and Na (EDX analysis on Fig. 9).

Meat and bone meal laboratory ash (MBM-LA) had a broad particle size distribution (Fig. 7) ranging between 1 μm and 2 mm. The grains were heterogeneous and angular (Fig. 10), but no spherical particles were found. This could be due to the incineration process, which was very different than for the industrial by-products (industrial rotary furnace).

The average densities of MBM-BA (2940 kg/m^3), washed MBM-FA (2880 kg/m^3), MBM-LA (3040 kg/m^3) and crude MBM-FA (2610 kg/m^3) are in accordance with their mineralogical compositions. MBM-BA and washed MBM-FA are a mixture of hydroxyapatite (3200 kg/m^3) and whitlockite (2860 kg/m^3), while MBM-LA mainly contains hydroxyapatite. The lower density of crude MBM-FA is due to the presence of salts having lower densities (2200 and 1990 kg/m^3 for NaCl and KCl, respectively).

3.3. Leaching behavior

Table 5 reports the concentrations of leached elements for the ashes according to European standard EN 12-457. MBM-LA, obtained from specific incineration, released much smaller amounts of heavy metals than other ashes. Moreover, it can be observed that, for MBM-BA, washed MBM-FA and MBM-LA, the leachate quantities were quite low compared to the total amount of elements initially present in the ashes (Table 3). Only crude MBM-FA released a significantly high amount of heavy metals, due to their higher solubility.

As these ashes are usually considered as waste materials, these results can be compared to the threshold values given in European regulations [55,56] concerning the classification of waste to be landfilled. Table 5 categorizes the ashes according

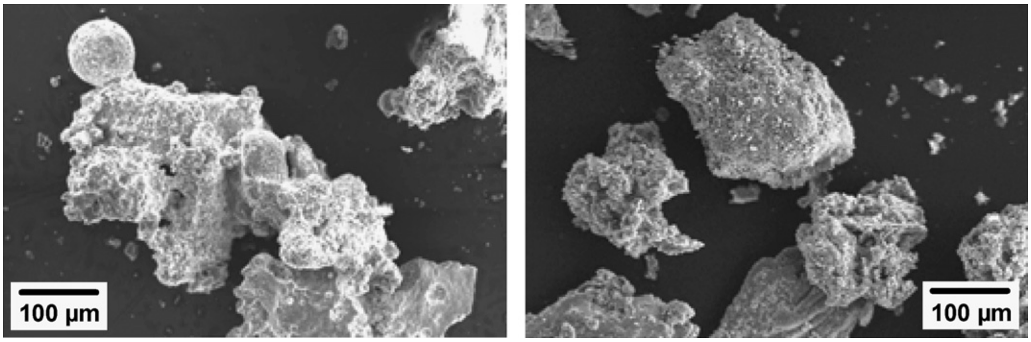

Fig. 8. Scanning electron microscopy of MBM-BA particles.

to the amount of element leached in regard to European waste acceptance criteria for landfills.

The small quantities of elements leached by MBM-LA (laboratory ash) allowed us to classify this ash as inert waste. MBM-BA (industrial bottom ash) can be considered as inert waste too, except as far as chromium (Cr) is concerned. For washed MBM-FA, the leached concentrations of seven elements are sufficiently low to allow them to be included in the inert category. Only zinc (Zn) and antimony (Sb) are in the non-hazardous (nh) and hazardous (h) categories, respectively. Finally, in the

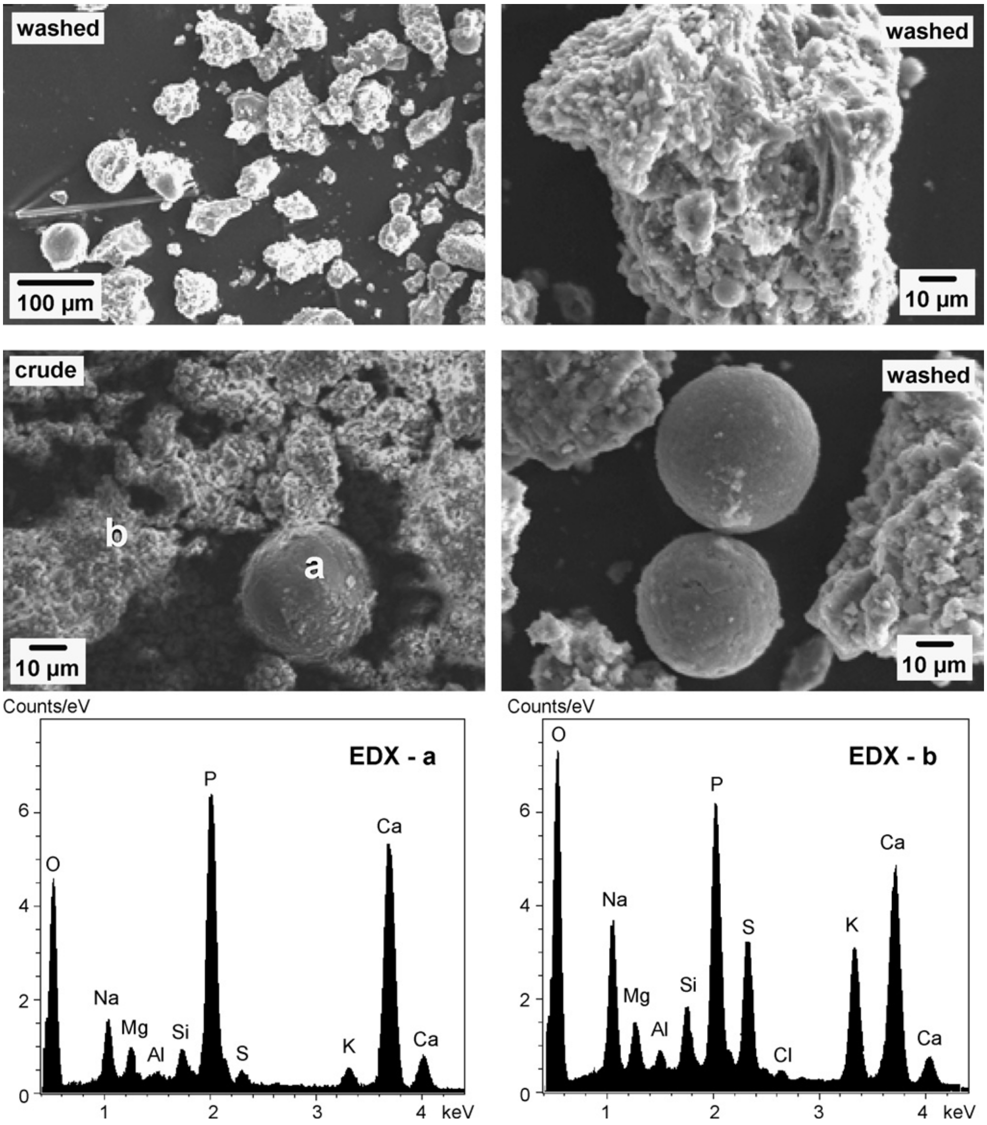

Fig. 9. Scanning electron microscopy and EDX analysis of crude and washed MBM-FA particles.

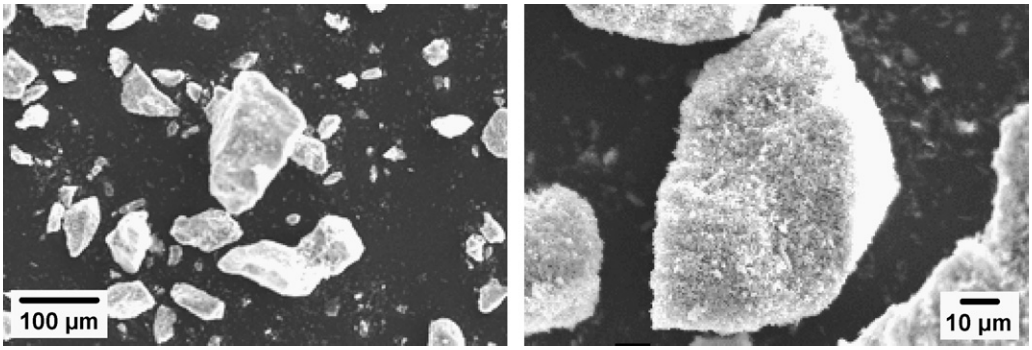

Fig. 10. Scanning electron microscopy of MBM-LA particles.

Table 5
Leaching behavior (EN 12-457) of MBM-BA, crude and washed MBM-FA and MBM-LA (μg/kg), compared to European waste acceptance criteria in landfill [55,56]

	Waste acceptance criteria [55,56]			MBM ashes							
	Inert (i)	Non-hazardous (nh)	Hazardous (h)	MBM-BA		Crude MBM-FA		Washed MBM-FA		MBM-LA	
As (μg/kg)	500	2,000	25,000	3	i	5,972	h	354	i	1	i
Ba (μg/kg)	20,000	100,000	300,000	999	i	855	i	148	i	34	i
Cd (μg/kg)	40	1,000	5,000	8	i	160	nh	8	i	0.1	i
Cr (μg/kg)	500	10,000	70,000	1104	nh	7,809	nh	391	i	146	i
Cu (μg/kg)	2,000	50,000	100,000	185	i	43,073	nh	104	i	1	i
Ni (μg/kg)	400	10,000	40,000	58	i	881	nh	29	i	1	i
Pb (μg/kg)	500	10,000	50,000	38	i	5,868	nh	31	i	<1.2	i
Sb (μg/kg)	60	700	5,000	28	i	7,085	h[a]	1884	h	1	i
Zn (μg/kg)	4,000	50,000	200,000	523	i	301,064	h[a]	4070	nh	<28	i

[a] Leaching concentration higher than hazardous criterion. Stabilization or washing treatment is needed.

case of crude MBM-FA, a lot more elements are released compared to the other ashes. The release of cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni) and lead (Pb) leads to a classification of crude MBM-FA as non-hazardous (nh) waste (hazardous for arsenic). Antimony (Sb) and zinc (Zn) contents are higher than the hazardous (h) criteria. In that case, stabilization or a washing treatment is necessary for these two elements. This preliminary environmental study highlights the advantage of specific incineration (MBL-LA) compared to co-incineration.

From above, it can be assumed that, except for crude MBM-FA, ways of reusing these ashes other than disposal in landfill could probably be envisaged.

3.4. Preliminary evaluation of reuse of MBM ashes

According to the major characteristics found in this study, a few examples of the possible reuse MBM ashes are given below:

- Use of MBM ashes as raw materials for the phosphate industry

  Since the composition, and especially the amount of phosphorus, is similar to the one found in natural phosphate rocks, and the heavy metal content (Pb or Cd) is often lower, MBM ashes could probably be used as a phosphorus source for the industry (phosphoric acid production, manufacturing of fertilizer, animal food, washing powder ...). Production of phosphoric acid from laboratory MBM ashes has been demonstrated at a laboratory scale [57]. Re-utilization of ashes in fertilizer manufacture could also be possible, since nearly 90% of the phosphoric acid production is used for the manufacture of fertilizer. At last, fertilizing action of soil amended with crude ashes has been observed on tobacco elongation [58], probably induced by high phosphate content. Additional studies will be carried out to investigate the influence of combustion condition on the formation of phosphate phases during ash incineration, in order to control phosphates dissolution, and thus phosphates biodisponibility in soil.
- Use of MBM ashes to stabilize waste by phosphatation processes

  Phosphatation processes are used to chemically stabilize heavy metals contained in materials, such as polluted soils and waste [59]. These heavy metals usually precipitate in new mineral forms, which are less leachable.
- Use of MBM ashes to remove and immobilize heavy metals

  Deydier et al. [26] studied the potential for immobilizing lead from aqueous effluents by means of MBM ashes. It was found that, due to its apatite content, MBM ash could remove 257 mg lead/(g ash) in less than 3 h, with a remaining lead concentration in solution lower than 0.1 ppb. Mouchet et al. [60] showed, using *Xenopus laevis*, that MBM ash led to a reduction or an inhibition of the toxic and genotoxic potential of lead in water. This research could be extended to other hazardous metals, such as cadmium or mercury, and to other applications requesting immobilization of metals. The study of other applications will imply the evaluation of the sorption stability of heavy metal under various environmental conditions, such as low or high pH (for instance in concrete).

- Use of MBM ashes in construction materials

  Cyr and Ludmann [31] and Collins [61] showed the potential of using MBM as a substitute for sand in mortar and concrete. However, considering their low amounts of Si, MBM ashes cannot be considered as pozzolanic material. Technological and environmental assessments are still needed before any industrial application. This will represent a part of our future work. Other uses, such as geotechnical and roadwork applications could also be envisaged.

4. Conclusion

This paper has presented a characterization of four meat and bone meal (MBM) ashes from different sources. The following results were found:

- Three of the ashes – MBM-LA (laboratory ash), MBM-BA (industrial bottom ash) and washed MBM-FA (industrial fly ash washed with water) – contain up to 47% of calcium and phosphorus, mainly as whitlockite and hydroxyapatite. Trace element contents are below 0.6% and industrial ashes contain much more hazardous element than laboratory ash. Major and trace compositions are near those found for natural phosphate rocks. The amounts of leached elements are low, especially for laboratory ash.
- Crude MBM-FA has a quite different composition than other ashes, since it has a significantly high content of sulfates, chlorides and alkalis (Na and K). These elements are present as soluble salts produced by the stream treatment at the plant and they represent almost 50% by mass of the total ash. High amounts of heavy metals are leachable.
- The results of the leaching tests highlighted the benefit of specific incineration of meat and bone meal. According to the European classification of waste to be landfilled, the laboratory ash MBM-LA can be classified as inert waste. MBM-BA and washed MBM-FA are mostly inert. Only crude MBM-FA is highly leachable and needs stabilization or washing treatment to enter the category of hazardous waste at least.

According to the characterization results presented in this paper, other possibilities than landfill seem possible for giving value to the ashes, mainly because of the low hazardous element content of three of the four ashes. However, extensive environmental and technical characterizations of these ashes would be required before any application.

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