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1 **Production of Portland cement clinker from French Municipal Solid Waste Incineration**  
2 **Bottom Ash**

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11

12 **Abstract**

13 The amount of bottom ashes generated from the municipal solid waste incineration is increasing  
14 considerably. Therefore their recycling is necessary in order to limit the landfilling that presents  
15 environmental issues. The aim of this paper is to recycle Municipal Solid Waste Incineration Bottom  
16 Ash from the north of France; as a secondary raw material for Portland cement clinker production. In  
17 this order Municipal Solid Waste Incineration Bottom Ash is characterized and then used to substitute  
18 raw materials for clinker production at laboratory scale. Substitutions rates up to 12.4% have been  
19 tested. The produced clinkers have been characterized by X-Ray Diffraction and the crystalline phases  
20 were quantified by Rietveld analysis. The microstructure has been studied by scanning electronic  
21 microscopy. After adding gypsum, the compressive strengths of the corresponding cements were  
22 measured at 1, 7 and 28 days. The mineralogical composition of the 28 days hydrated cement pastes  
23 were studied by X-Ray Diffraction. The results show that up to 12.4% of Portland cement raw  
24 materials can be replaced by the Municipal Solid Waste Incineration Bottom Ash without changing the  
25 mineralogical composition. In addition the compressive strengths of the cement pastes produced with  
26 Municipal Solid Waste Incineration Bottom Ash are equivalent to the one without bottom ash.

27 **Keywords:** Clinker; Compressive strength, Municipal Solid Waste Incineration Bottom Ash, Recycling

## 28 **1 Introduction**

29 The cement industry is responsible for more than 6% of the total anthropogenic greenhouse gases  
30 emissions. In fact the production of Ordinary Portland Cement "OPC" generates 842 kg CO<sub>2</sub>/t of  
31 clinker [1][2][3][4][5]. In addition to its huge energy consumption, the cement industry uses large  
32 amounts of raw materials for cement production [6]. Therefore the replacing of raw materials in the  
33 clinker raw meal by waste as secondary material, gains a lot of attention [2][7][8][9]. This replacement  
34 allows not only to preserve the natural resources and to recover wastes, but also to reduce the CO<sub>2</sub>  
35 emissions. Different types of wastes have been studied in the literature in order to produce cement,  
36 and mainly OPC cement, such as red mud [10], steel slag [11], sediments [12][13], recycled concrete  
37 aggregate [14], oil based mud cutting [15], oyster and scallop shell [16] etc.

38 In the European Union, the Municipal Solid Waste (MSW) production is significantly increasing. In  
39 2015, each inhabitant generated about 477 kg of MSW per year [17] [18]. The incineration presents  
40 the most common method to treat these wastes as an alternative to landfilling[19] and reduces  
41 between 70 and 90% the volume of wastes [20][21]. The MSWI ash is a by-product from the  
42 combustion of MSW [22][21][23][24][25]. Two types of ashes are produced following the incineration  
43 operation: bottom ash and fly ash. The recycling of these ashes is a concern especially that their  
44 quantities are increasing considerably and due to their highly variable composition.

45 The MSWI bottom ash (MSWI BA) represents 75-80% of the produced ashes [26][27][28]. Nowadays,  
46 the landfilling presents the main option for MSWI BA disposal [29][30]. However, the landfill causes the  
47 pollution of the groundwater and contaminates the soil in addition to the limited land space and the  
48 problems related to the disposal cost and the regulation [31][32][33]. The literature describes different  
49 methods to recycle the MSWI BA in civil engineering. The latter has been used as supplementary  
50 cementitious materials and pozzolanic material [29][27][34][35], as an aggregate replacement  
51 [19][28][36][37] or in alkali activated materials as a precursor [20][38][39], as a road based material  
52 and in road construction [40][41][42].

53 The chemical composition of MSWI BA contains CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> [43][44]. This  
54 composition makes the use of MSWI BA, as a secondary raw material, for clinker production  
55 possible[45]. Li et al. analyzed different fraction from MSWI BA from Beijing to produce a type II  
56 Portland cement and shows that 9% of this waste could be added to the raw meal [46]. Pan et al. also  
57 used MSWI fly ash and bottom ash, after washing with water/acid as a pre-treatment, to produce  
58 clinker by incorporating 1.75 and 3.5% respectively in the raw meal [47]. The percentages of  
59 incorporation were determined based on the chloride content in the ashes in order to respect the limit  
60 of chloride of 100 ppm required by the cement plant in Taiwan. They showed that this incorporation did  
61 not affect the compressive strength and the cement produced is conformed to the Chinese National  
62 Standard of type II Portland cement [47].

63 It is important to note that the MSWI BA has a very heterogeneous composition depending on several  
64 factors such as the waste origin, the incineration process, the incinerator used, the pre-treatment  
65 applied, etc. [48][49][50]. Therefore the percentage of substitution in the clinker raw meal differs from  
66 one to another MSWI BA. Until today, there are no studies dealing with the use of MSWI BA generated  
67 in France, as a secondary raw material for clinker production. Therefore the aim of this study is to use  
68 Municipal Solid Waste Incineration Bottom Ash from the north of France, as a raw material in the OPC  
69 clinker production. First a reference OPC clinker is produced without adding MSWI BA. Then 2  
70 substitution rates of MSWI BA are applied: 5% and a second one corresponding to the maximum  
71 amount of MSWI BA that could be incorporated while respecting the targeted composition of the  
72 reference clinker. The mechanical properties of the resulting cement are compared to reference OPC  
73 cement produced as well as the hydration products.

## 74 **2 Materials and methods**

75 The materials used in this study for the clinker production are the chemical reagents: CaCO<sub>3</sub>, SiO<sub>2</sub>,  
76 Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> and the MSWI BA from the north of France.

### 77 **2.1 MSWI BA characterization**

78 The MSWI-BA used in this study originates from the recycling platform RMN-PréFerNord located in  
79 Fretin in the region of "Hauts-de-France" in France. This platform treats between 150,000 and 180,000  
80 tons yearly and is considered to be among the largest in France in terms of quantities and the  
81 techniques used for the process of preparation of the MSWI-BA. MSWI-BA was subjected to a

82 maturation period of two to four months in open air and was considered recyclable in the field of roads'  
 83 construction according to the French regulation of 18 November 2011 [51]. The fraction 0-2 mm of  
 84 Municipal Solid Waste Incineration Bottom Ash (MSWI BA) is crashed and then sieved at 100  $\mu\text{m}$ . The  
 85 mineralogical characterization was made by X-ray diffraction (XRD) using a diffractometer Bruker D2  
 86 with Cu K $\alpha$  radiation. The X-ray patterns were acquired in the  $2\theta$  (10-80  $^\circ$ ) with a step of 0.02 $^\circ$  and 1 s  
 87 per step. The chemical composition was analyzed by X-ray fluorescence (XRF). The particle size  
 88 distribution was determined using the laser granulometer COULTER type LS 230.

## 89 2.2 Clinker production at laboratory scale

90 Three Portland clinkers are produced in the laboratory with different percentage of substitution by  
 91 MSWI BA. The first is a reference clinker referred by OPC0 produced using analytical reagents  
 92 ( $\text{CaCO}_3$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$  and  $\text{Fe}_2\text{O}_3$ ) only. The theoretical mineralogical composition of OPC0 is shown in  
 93 table 1. This composition was chosen according to the study of Gineys et al [8] in order to produce an  
 94 Ordinary Portland Cement.

95 **Table 1 : Theoretical composition of the targeted Portland clinker**

$\text{C}_3\text{S}$ (wt. %)	$\text{C}_2\text{S}$ (wt. %)	$\text{C}_3\text{A}$ (wt. %)	$\text{C}_4\text{AF}$ (wt. %)	C (wt. %)
65%	18%	8%	8%	1%

96

97 For the MSWI BA based clinker, the solver option in Microsoft Excel was used to adjust and calculate  
 98 the amount of the different raw materials [14] when substituting with MSWI BA. This option uses the  
 99 chemical composition, determined by XRF for the different raw materials and MSWI BA (% wt. of Ca,  
 100 Si, Al, Fe), with the aim to respect the targeted cement criteria represented in table 1.

101 The first substitution rate in the clinker raw meal by MSWI BA corresponds to 5% (OPC5). The second  
 102 one corresponds to the maximal amount of MSWI BA that could be incorporated in the raw meal while  
 103 respecting the theoretical composition of the targeted Portland cement.

104 Table 2 shows the mixes designs of the 3 clinker raw meals obtained by solver and the percentage of  
 105 each component to add, in order to reach the theoretical composition of table 1. As it can be seen from  
 106 the table 2, the maximum amount of MSWI BA that could be incorporated in the raw meal is controlled  
 107 by the  $\text{Fe}_2\text{O}_3$  content (OPC12.4). Adding more than 12.4% of MSWI BA (maximum value) in the raw  
 108 meal provides more  $\text{Fe}_2\text{O}_3$  than needed and consequently the resulting clinker composition differs  
 109 from the theoretical composition of the targeted Portland clinker.

110

**Table 2: Mixes designs for the 3 produced clinker raw meals**

Constituents	$\text{CaCO}_3$ (wt. %)	$\text{SiO}_2$ (wt. %)	$\text{Al}_2\text{O}_3$ (wt. %)	$\text{Fe}_2\text{O}_3$ (wt. %)	MSWI BA (wt. %)
OPC0	79.98	15.35	2.92	1.75	0
OPC5	77.45	14.11	2.39	1.05	5
OPC12.4	73.71	12.28	1.61	0	12.4

111

112 The method to produce clinker consists to mix all materials together by adding water to better  
 113 homogenize. The mix is then dried at 105 $^\circ\text{C}$  and pressed at 5 kN into pellets to obtain a better  
 114 clinkering process. Then the pellets are fired up 30 min at 200 $^\circ\text{C}$  then to 1450  $^\circ\text{C}$  with a rate of 10 $^\circ\text{C}$ .  
 115 After 15 min of burning at the clinkering temperature, the clinker was cooled in the furnace. The  
 116 obtained clinkers are ground until a Blaine specific area of 4500  $\text{cm}^2/\text{g}$ . To produce cements, gypsum  
 117 was added to the clinker using equation 4 [52]:

118 Amount of gypsum used =  $\text{Al}_2\text{O}_3$  content \* [0.6/101.96] \* [80/0.461] (equation 4)

119 Where, 101.96 = mol. wt.  $\text{Al}_2\text{O}_3$ ; 80 = mol. wt.  $\text{SO}_3$ ; 0.461 = mol. ratio  $\text{SO}_3$ /natural gypsum used (for  
 120 pure gypsum 80/172 is 0.466)

## 121 2.3 Clinker and cement paste characterization

122 The mineralogy of the synthesized clinkers was studied using X-ray diffraction (XRD). A Bruker D2  
 123 with Cu K $\alpha$  radiation was used. The X-ray patterns were acquired in the  $2\theta$  (10-80  $^\circ$ ) with a step size  
 124 of 0.02  $^\circ$  and 1 s per step. A Rietveld analysis was also conducted using TOPAS software in order to  
 125 quantify the crystalline phases.

126 The Microscopic observations were conducted on polished section of clinkers using SEM type Hitachi  
 127 S-4300SE/N. Local chemical analyses were conducted using energy dispersive X-ray spectrometer  
 128 (EDS) with a Thermo Scientific Ultra Dry EDS detector coupled with the SEM. The polished sections  
 129 were made by vacuum impregnating a clinker monolith in an epoxy resin. After hardening, the samples  
 130 were polished with ethanol and then coated with carbon.

131 The reactivity of the cement pastes was followed by isothermal calorimetry performed at 20°C. The  
 132 water/cement ratio used was 0.5. The calorimeter was a home-made calorimeter using fluxmeters that  
 133 allowed the calorimeter to equilibrate in less than 5 min [53].

134 The hydrates of the 4 different cement pastes are identified by XRD analysis at 28 days after stopping  
 135 the hydration by immersing the cement pastes - already grounded into powder – in ethanol. After few  
 136 minutes of mixing with ethanol, a filtration is done using the Buchner filter. The powder is then  
 137 collected and dried in the oven at 50°C.

138 The compressive strength was determined on cement paste small cubes 1\*1\*1 cm (due to the limited  
 139 quantities of cement produced in the laboratory according to [51]) made of cement pastes with a  
 140 water/cement ratio (w/c) of 0.5. Cement and water were manually mixed. The filling of the molds  
 141 (polytetrafluoroethylene (PTFE) molds) was performed in two steps on a vibration table. The molds  
 142 were kept for 24 h at 100% relative humidity at 20 °C. The paste cubes were demolded after 24 h and  
 143 curing was continued at 100% relative humidity at 20 °C. The compressive strength was measured  
 144 after 1, 7 and 28 days [53], [54].

### 145 3 Results and discussions

#### 146 3.1 MSWI BA characterization

147 Table 3 presents the bottom ash composition as well as the soluble salts. The results show that MSWI  
 148 BA contains all the necessary major elements for the clinker production (Ca, Si, Al and Fe).

149 **Table 3: Bottom ash composition**

Element	LOI 950°C	O	Ca	Fe	Al	Si	P	S	Cl	Pb
Percentage (%)	13.99	34.06	18.91	9.45	5.57	11.06	0.76	0.94	0.25	0.17
Element	K	Na	Ti	Cr	Mn	Mg	Cu	Zn	Ba	
Percentage (%)	0.6	1.25	0.44	0.1	0.19	1.13	0.24	0.63	0.11	
soluble salts (mg/kg)										
Fluoride					<20					
Chloride					2740					
Sulphate					5059					

150

151 The X-ray diffraction (figure 1) for MSWI BA shows that the principal phases are quartz, calcite, with  
 152 some minor phases such as hematite, gehlenite etc.

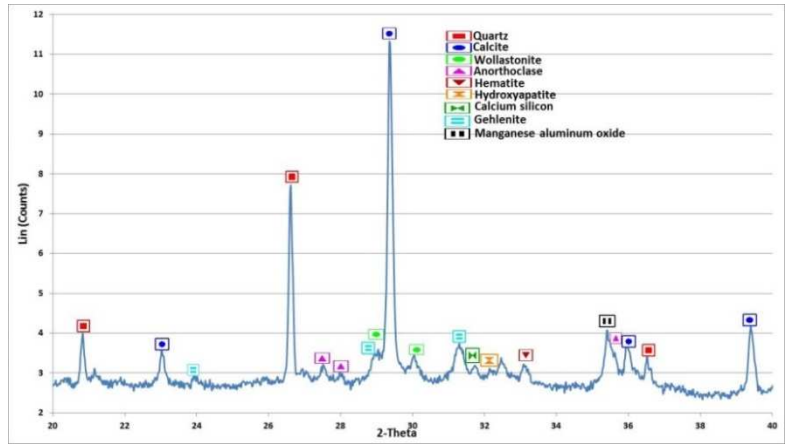


Figure 1: X-ray pattern for MSWI BA

153  
154

155 The particle size distribution of MSWI BA is represented in figure 2. The results show that 90% of  
156 particles are inferior to 70  $\mu\text{m}$ . In fact the finesse of the raw materials is important in order to have a  
157 better reactivity.

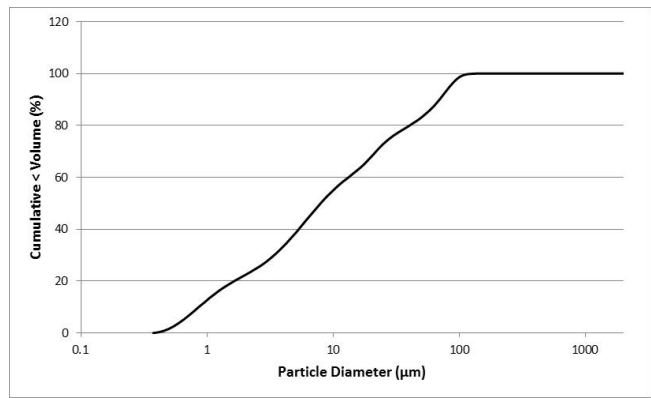


Figure 2: Particle size distribution for MSWI BA

158  
159

## 160 3.2 Clinkers characterization

### 161 3.2.1 Mineralogical and chemical analyzes

162 The OPC0 reference clinker characterization by XRD is presented in figure 3. The result shows the  
163 presence of the 4 crystalline phases of a Portland clinker,  $\text{C}_3\text{S}$ ,  $\text{C}_2\text{S}$ ,  $\text{C}_4\text{AF}$  and  $\text{C}_3\text{A}$ . The pattern shows  
164 also that no secondary mineral phases are produced. Therefore the raw meal composition, the clinker  
165 preparation process at the laboratory scale and the burning temperature are suitable for this study.

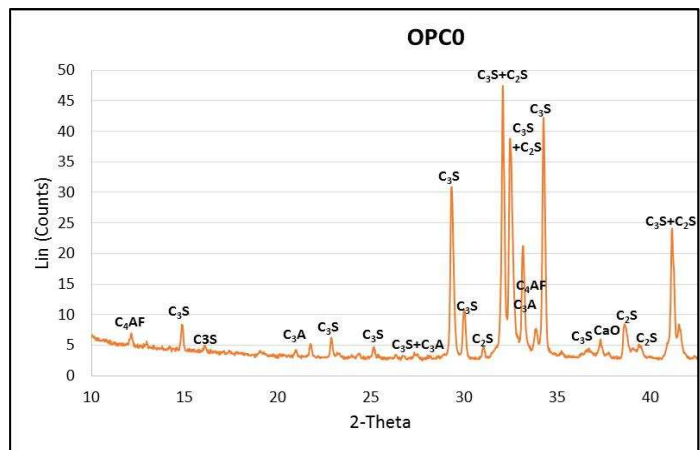
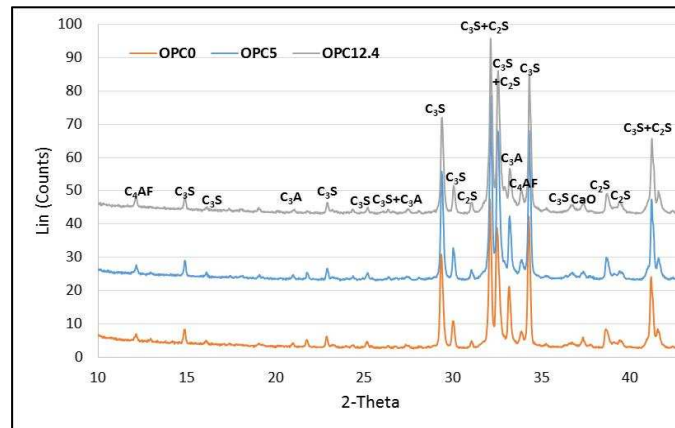


Figure 3: XRD patterns of the reference clinker OPC0

166  
167

168 The MSWI BA based clinkers OPC5 and OPC12.4 are characterized and compared to the reference  
 169 clinker. The results are shown in the figure 4. As it can be seen from the patterns, the 2 MSWI BA  
 170 based clinkers, OPC5 and OPC12.4 present the same mineralogical phases as the reference clinker  
 171 OPC0. Consequently the partial substitution of the raw materials by MSWI BA does not modify the  
 172 mineralogical composition of the produced clinkers.



173  
 174 **Figure 4: XRD results for the reference clinker OPC0 and for the MSWI BA based clinker OPC5 and OPC12.4**

175 The three produced clinkers were subjected to an elementary analyzes by XRF in order to detect the  
 176 presence of heavy metals and alkalis (Table 4). The results show that some heavy metals (Zn) and  
 177 alkali (Na) slightly increases while increasing the MSWI BA substitution. The presence of these heavy  
 178 metals could have an influence on the hydration mechanisms and on the setting time of the cement by  
 179 forming a heavy metal hydroxide on the surface of the anhydrous cement grains, as suggested by  
 180 Gineys et al. studies [55][56].

181 **Table 4: XRF analyzes for the 3 produced clinkers**

Element (%)	L.O.I (%)	O	Ca	Si	Fe	Al	Na	Mg	P	Ti	Zn
OPC0	3	38.8	47.3	9.9	1.8	2.2	-	-	-	-	-
OPC5	2.7	38.4	47.3	9.9	1.9	2.0	0.2	0.1	<0.1	<0.1	<0.1
OPC12.4	2.6	38.7	46.4	10.1	1.9	2.0	0.2	0.2	0.1	0.1	0.1

182 In order to quantify the crystalline phases in the 3 synthesized clinkers, Rietveld analysis was  
 183 conducted. The results are represented in the table 5 and show that adding MSWI BA in the raw meal  
 184 produces a clinker with slightly less C<sub>3</sub>S comparing to the reference clinker. This could be due to the  
 185 consideration in the calculation method that the four clinker phases are in their stoichiometric state  
 186 which is not quite realistic especially when incorporating wastes into the raw meal where the phases  
 187 can accommodate substitute ions [57]. Same results was obtained by Clavier et al. 2021 [43] when  
 188 incorporating bottom ash in the clinker. This was attributed to the operational variations associated  
 189 with lab-scale clinker production. In fact the C<sub>3</sub>S tends to revert to C<sub>2</sub>S when clinker is cooled too  
 190 slowly and therefore the speed of cooling showed be considered. In addition the Portland cement  
 191 chemistry is complex, therefore this complexity increases when a replacing the raw materials by a  
 192 heterogeneous material such as MSWI BA. The latter contains, as shown in table 3, some metallic  
 193 elements (i.e. Cu, Zn, Mg, Cl...) that could cause a reduction in the mineralization temperature,  
 194 favoring therefore the formation of C<sub>2</sub>S over the C<sub>3</sub>S phase[58]. Concerning the residual lime, its  
 195 content is between 0.05% and 0.21% (table 5) which confirms that the clinkering was complete  
 196 because these values are lower than what is specified in the standard NF EN 196-2. In addition,  
 197 according to the standard there is no risk due to these low free lime contents (<0.5%).

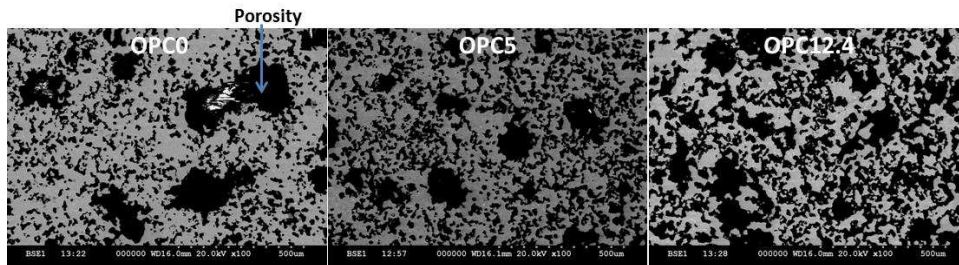
198 **Table 5: Rietveld analysis for the 3 clinkers: OPC0, OPC5 and OPC12.4**

	C <sub>3</sub> S (wt. %)	C <sub>2</sub> S (wt. %)	C <sub>4</sub> AF (wt. %)	C <sub>3</sub> A (wt. %)	CaO (wt. %)	GoF
OPC0	76.14	12.27	3.5	7.88	0.21	1.65
OPC5	74.01	15.21	4.07	6.66	0.05	1.44
OPC12.4	72.12	19.60	4.13	4.09	0.06	1.45

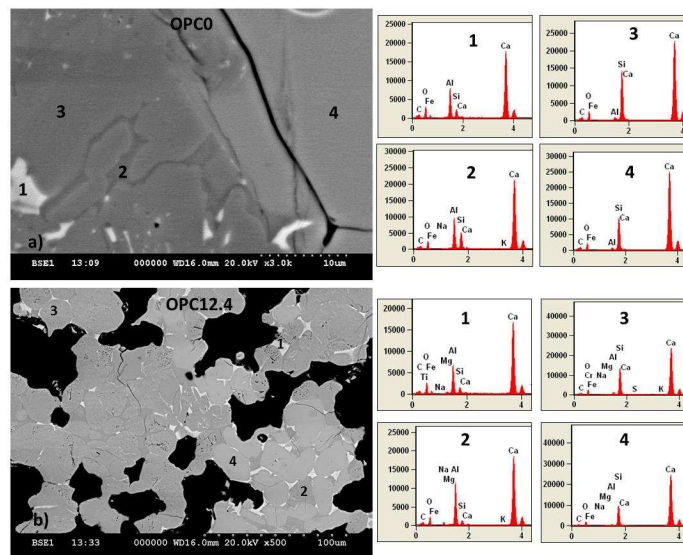
200 **3.2.2 Microstructure observation**

201 The microstructure of the 3 produced clinkers was observed by SEM/EDS on polished sections (figure  
202 5). By comparing the 3 samples, it can be seen that the porosity (black areas) of the clinker matrix  
203 increases while increasing the incorporation percentage of MSWI BA. According to the literature, this  
204 behavior could be due to the presence of heavy metals (i.e. Zn) that could change the viscosity of the  
205 interstitial liquid phase of clinkers during the sintering process. In fact, zinc acts as a mineralizer [59],  
206 therefore the porosity of the clinkers could be influenced [60] [61].

207 **Figure 5: Microstructural observations of the 3 clinkers: OPC0, OPC5 and OPC12.4**



208  
209 In order to identify the mineralogical phases of clinkers, elemental analyzes by EDS were conducted  
210 on OPC0 and OPC12.4 (figure 6). In both clinkers, C<sub>4</sub>AF (point 1), C<sub>3</sub>A (point 2), C<sub>2</sub>S (point 3) and C<sub>3</sub>S  
211 (point 4) were identified. The alite grains appeared to be angular whereas the belite one round. The  
212 clinkers, with and without BA, present in general almost a similar microstructures.



213 **Figure 6: SEM/EDS spectra of the 2 clinkers OPC0 and OPC12.4**

214  
215 **3.3 Calorimetric study**

216 The hydration reactions of the cement paste are exothermic and can be monitored by following the  
217 rate of heat release using an isothermal calorimeter. Figure 8 shows the calorimetric curves for the  
218 three cement pastes with and without BA incorporation: OPC0, OPC5 and OPC12.4. It can be seen  
219 from the results that the three cement pastes have a similar curve shape. Three peaks were formed  
220 during the first 36 hours of hydration. The first peak corresponds to the dissolution of the anhydrous  
221 grains and appears immediately after adding water to cement. Then an induction period with low  
222 thermal activity was observed for the three cement paste before appearance of the second peak. The  
223 latter corresponds to the acceleration of the silicates and aluminates hydration and the formation of C-  
224 S-H and ettringite. A third peak is formed after the gypsum depletion and the transformation of  
225 ettringite to monosulfoaluminate hydrate.

226 By comparing the three curves a main difference can be detected related to the initial setting time. In  
227 fact the setting of OPC0 begins approximately 1 hour before OPC5 and OPC12.4. This could be due  
228 to the trace elements (i.e. Zn) that are present in the MSWI BA based clinkers as already shown in the  
229 XRF results (table 4). According to previous studies, Zn is well known to have a retarder effect on the



230 cement paste hydration [56][55]. In addition, the presence of alkalis such as Na could also induce a  
231 retardation effect [62].

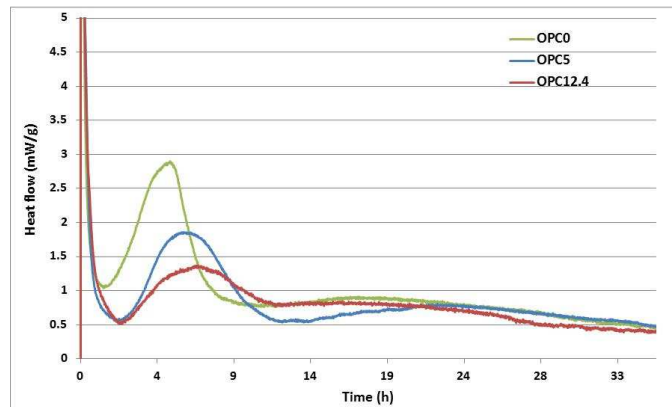


Figure 7 : The heat release for the three cement pastes: OPC0, OPC5 and OPC12.4

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233

### 234 3.4 Mechanical performances

235 The compressive strength is measured in order to evaluate the mechanical performances of the  
236 produced cement. Figure 7 represents the compressive strength at 1, 7 and 28 days for the three  
237 cement pastes: OPC0, OPC5 and OPC12.4. These results show that at early age (1 day) the  
238 compressive strengths is lower when MSWI BA is added (19.5, 14 and 10.7 MPa for OPC0, OPC5  
239 and OPC12.4 respectively). This could be related to the retardation effect observed by isothermal  
240 calorimetry at 1 day caused by the heavy metals and alkalis as previously shown in figure 8. This  
241 could be related also to the amount of  $C_3S$  in the clinker (table 4) that is a slightly higher in the clinker  
242 containing less MSWI BA. In addition the presence of alkali such as sodium and potassium could also  
243 have a retardation effect on the hydration and influencing therefore the compressive strength [63].  
244 This difference in the compressive strength of the three cement pastes is less observed from day 7  
245 because the effect of the delay of the hydration appears at very short term. It can be concluded that  
246 using MSWI BA as a substitution for the raw materials for clinker production does not change  
247 significantly the compressive strength of the cement pastes especially after 7 days.

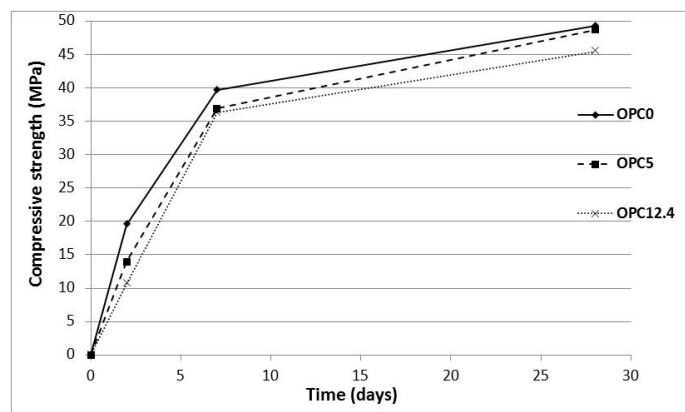


Figure 8: Compressive strength of the 3 cement pastes at 1, 7 and 28 days

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249

250 The mineralogical assemblages of the hydrated cement pastes at 28 days were studied by XRD  
251 analysis after stopping the hydration (figure 9). The results show that the Portlandite CH is the main  
252 crystalline hydrate. This phase comes from the hydration of  $C_3S$  and  $C_2S$ . The patterns show also the  
253 presence of Ettringite AFt coming from the reaction of  $C_3A$  with gypsum.

254 The diffractograms of the 3 cement pastes (reference and the 2 cement pastes with MSWI BA) are  
255 similar. Therefore adding MSWI BA in the raw meal to produce Portland cement does not modify the  
256 mineralogical assemblage of the hydrated cement pastes.

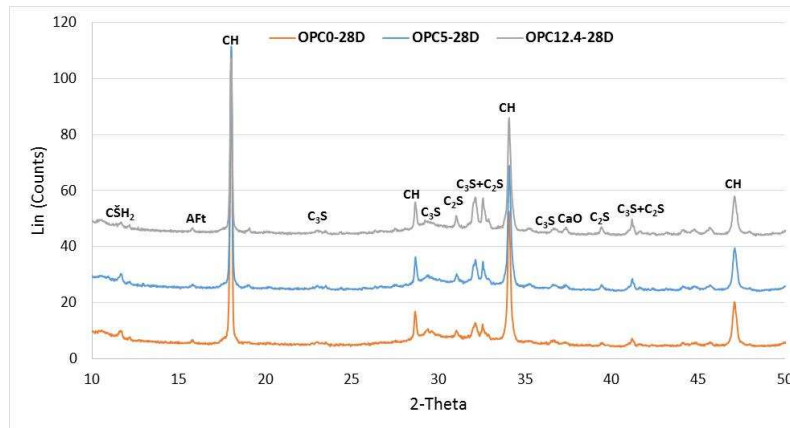


Figure 9: XRD analysis for the 3 cement pastes OPC0-28D, OPC5-28D and OPC12.4-28D at 28 days

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#### 259 4 Conclusion

260 The aim of this paper is to recycle the MSWI BA from the north of France, in the raw meal to produce  
 261 Portland clinker. To reach this target, MSWI BA was grinded and characterized in order to identify its  
 262 composition. In addition to the reference clinkers made with chemical reagents, two other clinkers  
 263 were synthesized: OPC5 with 5% of MSWI BA and OPC12.4 with 12.4% that represents the maximum  
 264 amount of substitution. It has been shown in this study that:

- 265 - MSWI BA contains the main oxides - CaO, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Fe<sub>2</sub>O<sub>3</sub> - needed for the clinker  
 266 production
- 267 - For the clinker composition chosen, the maximum amount of MSWI BA that could be  
 268 incorporated in the raw meal is controlled by the Fe<sub>2</sub>O<sub>3</sub> amount. The addition of 12.4% of  
 269 MSWI BA provides the total amount of iron oxide needed for the clinker production
- 270 - Adding MSWI BA in the raw meal for the clinker production does not affect the mineralogical  
 271 composition comparing to the reference clinker. The main phases of Portland clinker – C<sub>3</sub>S,  
 272 C<sub>2</sub>S, C<sub>4</sub>AF and C<sub>3</sub>A in addition to free lime are obtained for all produced clinkers
- 273 - The microstructure of the clinker with and without BA is quite similar despite the presence of  
 274 more porosity in the MSWI BA based clinker which could be due to the clinkering process and the  
 275 presence of some heavy metals
- 276 - The partial substitution of raw materials by MSWI BA provoked a delay of less than 1 hour in  
 277 the setting time which could be attributed to the presence of heavy metals and alkalis.
- 278 - The difference between the compressive strength of MSWI BA-based clinkers and the  
 279 reference are slight after 7 days of hydration.

280 Finally, this study reveals that the bottom ash could be recycled as a secondary raw material for  
 281 clinker production. The amount of bottom ash that could be recycled depends mainly on its  
 282 composition and the type of cement targeted.

283 In our case we conclude that the French bottom ash has different chemical composition from the  
 284 ones studied in the literature (coming from Taiwan and Beijing [46] [47]). With this type of bottom  
 285 ash, it is possible to recycle 12.4% in CEM I Portland cement after adapting the raw meal  
 286 composition and without applying a treatment for the bottom ash.

287 Given the large variability of the bottom ash composition, due to the type and the origin of wastes  
 288 that differs from a country to another, it is important to extend the study to investigate the  
 289 variability of the bottom ash composition from a batch to another and the effect that could have on  
 290 its possible use as a raw material for cement production. In addition it is interesting to follow in  
 291 further studies the durability of the cement pastes made from MSWI BA based clinkers in order to  
 292 have a complete vision on the behavior of these clinkers.

#### 293 Declaration of competing interest

294 The authors declare that they no known competing financial interests or personal relationships that  
 295 could have appeared to influence the work reported in this paper.

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