Conference paper
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The Behaviour of Finely Ground Bottom Ash in Portland Cement

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Abstract: The aim of this project was to assess the effects of finely ground MSWI bottom ash in Portland cement. Mortar mixes were prepared with 10% and 40% replacement of cement by ground IBA and then tested with regards to their material composition and engineering behaviour. IBA was found not to be inert, but showed some degree of reactivity. Replacement of cement with IBA was found to have no detrimental effects at low concentrations. This was not the case for 40% replacement, where cement replacement greatly affected strength, creep and drying shrinkage.

Bottom Ash			
Element	**Mass%**	**Element**	**Mass%**
SiO_2	28.26	BaO	0.528
CaO	21.95	NiO	0.519
Al_2O_3	13.63	TiO_2	2.7
Fe_2O_3	12.16	MnO	0.219
Na_2O	4.5	Co_3O_4	0.0839
K_2O	0.409	SrO	0.0549
MgO	1.19	ZrO_2	0.051
SO_3	1.42	WO_3	0.0482
P	1.34	SnO_2	0.0286
Cr_2O_3	1.31	PbO	0.0261
Cl	5.1	MoO_3	0.0251
ZnO	0.842	V_2O_5	0.0179
CuO	0.799	Sb_2O_3	0.0139

Table 1. Composition of Bottom Ash

1. Aims and Objectives

Every year, 30 million tonnes municipal solid waste (MSW) are produced. Increasingly, this waste is incinerated to recover its embedded energy. One of the by-products of incineration is Bottom Ash (IBA), which contributes about 20-30% by mass of the original waste feed, and is a material rich in silicon, calcium, aluminium and iron. Currently, much of this ash is sent to landfill, but alternative uses have been sought. The aims of this third year project were to investigate the behaviour of MWSI bottom ash in a Portland cement matrix as a partial cement replacement in civil engineering applications. The effects on strength, shrinkage, creep and setting times were investigated.

2. Method

The composition of the bottom ash used in this project is shown in Table 1. The as-received ash was sieved to remove large lumps and then ground to a fineness of 2μm to be used in mortar mixes. OPC mortars were prepared with OPC:water:sand ratios of 1:0.5:3 with bottom ash replacing the OPC by either 10% or 40% by weight. OPC pastes were prepared with water/solid ratios of 0.5 and similar levels of OPC replacement. An example of a mortar design mix can be found in Table 2. Note, the water/cement ratio was the same for any standard mix, excluding the mix to achieve standard consistence.

	OPC	OPC+10%BA	OPC+40%BA
Cement (g)	300	270	180
Bottom Ash (g)		30	120
Water (g)	150	150	150
Sand (g)	900	900	900
W/C ratio	0.50	0.56	0.83

Table 2: Example of a mortar mix design

Results

SEM examination of the bottom ash particles revealed angular particles often less than 5μm in diameter. Figure 1 shows the effect on paste morphology of the replacement of OPC with bottom ash. The effective increase in water/cement ratio led to an increase in the paste porosity. However, despite the increase in water/cement ratio, replacement of the OPC with BA led to a reduction in workability [1] (Table 3), most likely due to the high specific surface area of the BA, and its angular nature. This observation was confirmed by the standard consistence measurements (Table 4) performed according to the relevant standard [2]. With increasing replacement of OPC by BA there was an increased water demand.

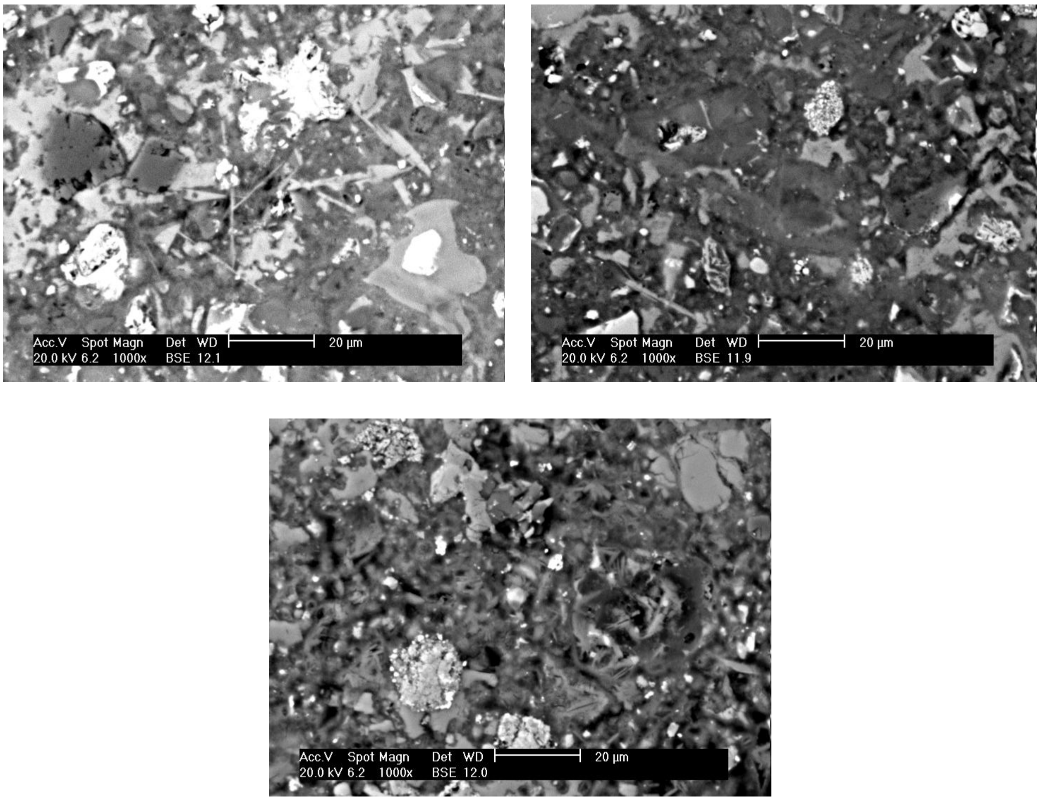

Figure 1. SEM of (a)OPC (b)OPC+10%BA (c)OPC+40%BA

Table 1. Flow Table Results

	OPC	OPC+10%BA	OPC+40%BA
R1	190 mm	168 mm	138 mm
R2	190 mm	165 mm	134 mm
average	190 mm	166.5 mm	136 mm

Table 2. Standard Consistence Design Mix

	OPC	OPC+10%BA	OPC+40%BA
Cement (g)	400	360	240
BA(g)		40	160
Water(g)	140	130	115
W/C ratio	0.35	0.36	0.48

The setting times were also measured according to the relevant standard [3] and are shown in Table 5. Setting time decreased slightly with 10% replacement, but then increased when 40% of the OPC was replaced. Replacement of the OPC with 10% of finely ground bottom ash may provide nucleation sites for hydration, together with an increased the W/C ratio favouring the transport of reactive elements [4]. Conversely, at 40% replacement, the release of large quantities of foreign elements may retard cement hydration.

Table 3. Summary of Setting Times

	OPC	OPC+10%BA	OPC+40%BA
Initial Setting Time	1h55	1h37	2h18
Final Setting Time	4h35	4h15	4h55

Hydration was then followed by conduction calorimetry, the results of which are shown in Figure 2. At low levels of replacement there is a higher maximum rate of heat evolution and more heat is generated than for a pure OPC mix, but the reverse is true at higher levels of replacement. This agrees with the setting time results mentioned above, i.e. low levels of replacement appear to accelerate hydration. At higher concentrations there is also an extra 'bump' on the curve showing the formation of secondary AFt possibly due to the incorporation of extra iron and aluminium from the bottom ash. Thus, it may be assumed that the bottom ash is not inert. This is supported by looking at the total heat evolution over the first 72 hours of hydration. Replacement of 40% of the OPC led to only about a 10% reduction in heat evolution.

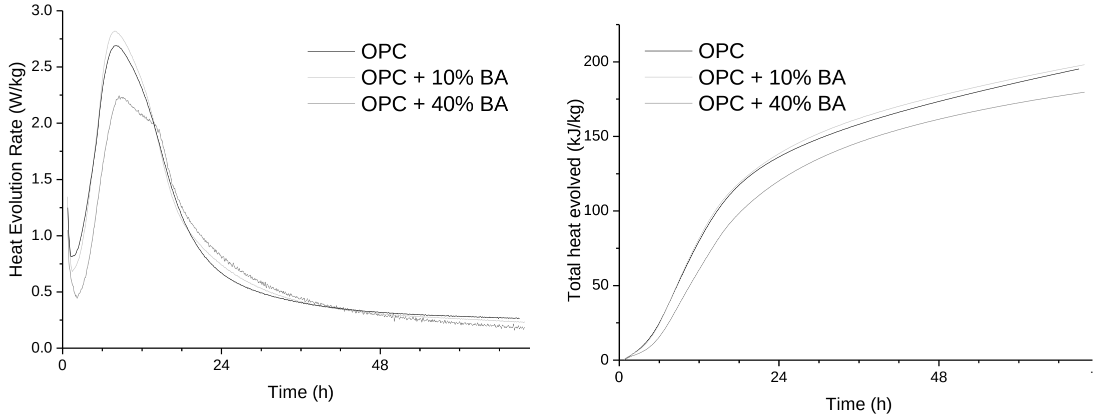

Figure 2. Heat Evolution Rate and Total Heat

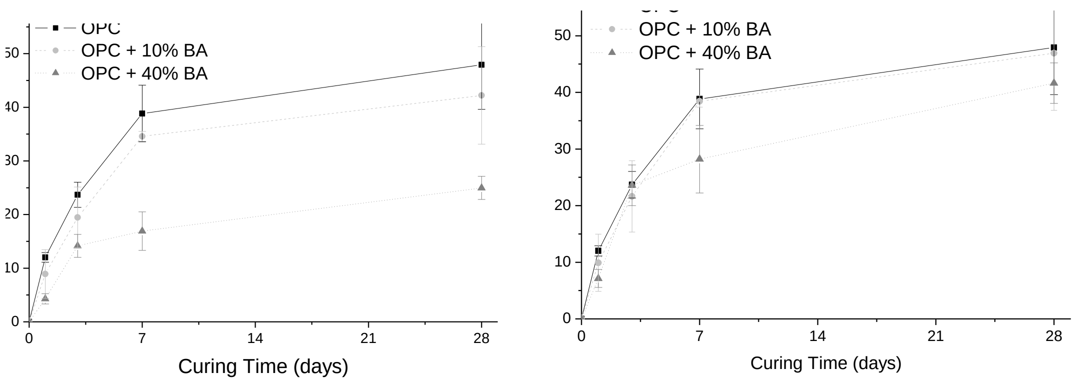

Figure 3. The Effect of OPC replacement by BA on Strength Development.
(The figure on the right shows the strength normalised to the cement content)

The effect of replacement on mortar strength was also investigated. Figure 3 shows how 10% replacement, leads to a slight reduction in strength, but the decrease is not statistically significant. However, replacement of 40% of the OPC by BA results in a marked reduction in strength. Figure 4 meanwhile shows the strength development normalised to OPC content. From this plot it can be seen that the slight reduction in strength with 10% replacement is due to the loss of OPC, whilst 40% replacement has a major effect due to both reduction in OPC content and in an increase in water/cement ratio. It is also worth noting that the differences in the curves are not apparent in the first three days of hydration, explaining the similarity in the calorimetry data shown in Figure 2.

Finally, both creep and shrinkage measurements were conducted on the two samples with differing levels of replacement. Table 6 shows the data obtained after 28 days. The strain is clearly seen to increase with increasing levels of cement replacement, being about three times greater for 40% replacement compared to the pure OPC mortar. This is due to the increased w/c ratio and the resultant increased porosity, as seen in the SEM micrographs.

Table 4: Amount of Strain due to Shrinkage and Creep after 28 days.

	Shrinkage	**Creep**	**Total**
OPC	2.8×10^{-4}	1.7×10^{-4}	4.5×10^{-4}
OPC + 10% BA	5.3×10^{-4}	2.9×10^{-4}	8.2×10^{-4}
OPC + 40% BA	6.3×10^{-4}	5.7×10^{-4}	12.0×10^{-4}

Conclusions

The research has shown that:

- Finely ground bottom ash particles increase water demand for a given workability.
- The rate of hydration is increased at low levels of replacement but retarded at higher levels. The increase in rate of hydration may be due to the presence of additional nucleation sites whilst retardation may be due to the presence of foreign elements.
- At high replacement levels bottom ash does not appear to be inert, with the possible apparent formation of secondary ettringite.
- Replacement of OPC with bottom ash reduces strength, but at low levels of replacement this is due primarily to the increase in water/cement ratio.
- Replacement of OPC with bottom ash also leads to increased susceptibility to creep and drying shrinkage, due to the increase in w/c ratio.

References

1. [1]BS 4551-1:1998: Methods of Testing Mortars, Screeds and Plasters
2 BS 4550-3.5:1978: Methods of Testing Cement – Standard Consistency
3 BS 4550-3.6:1978: Methods of Testing Cement – Setting Time
4 Olgun, A., *et al*., Effects of colemanite waste, cool bottom ash and fly ash on the properties of cement, *Cement and Concrete Research*, 2001, **31**, 491-494.