The Effects of Bottom Ash as a Partial Cement Replacement

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ABSTRACT

The cement industry accounts for 5% of the worldwide anthropogenic carbon dioxide emissions annually, a figure most likely to climb as cement production is expected to increase. In an attempt to reduce this figure, cement has been replaced by other materials presenting similar properties to OPC. 30 million tonnes of Municipal Solid Waste (MSW) are produced every year in the UK alone, and is often combusted to reduce the amount of waste sent to landfill and recover potential energy. The aim of this project was to see if bottom ash (BA), a by-product of the combustion of MSW, is a suitable cement replacement and see the possible effects it has at 10% and 40% replacement. Bottom ash was found to have some reactivity, but without greatly affecting the hydration process of OPC at 10% replacement. At 40% replacement however, the addition of BA greatly affected strength, creep and drying shrinkage.

Keywords: OPC; Bottom Ash; Strength; Creep; Shrinkage; Setting time.

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INTRODUCTION

Every year, approximately two billion tonnes of cement are produced, a figure that is likely to rise in the future. The production of cement comes with an important release of CO_2, the cement industry accounting for 5% of anthropogenic carbon dioxide emissions alone. These emissions come from different stages of the cement production – the calcination process of limestone, combustion of fossil fuels in the kilns, and from power generation[1]. In the hope of reducing the carbon footprint of the industry, cement has been partially replaced by other materials with similar hydration behaviour to OPC. Bottom ash is a by-product of the incineration of Municipal Solid Waste (MSW) to produce heat and power. Thirty million tonnes of MSW are produced every year in the UK alone[2]. Bottom ash typically represents 20 to 30% of the original waste feed by weight but only 10% by volume[3] and is usually disposed of to landfill after incineration. The aim of this project was to evaluate the effects of bottom ash as a partial cement replacement. OPC has been replaced by 10% and 40% bottom ash by weight in mortar and cement paste mixes. The effects on strength, creep and shrinkage, setting time have been evaluated.

EXPERIMENTAL METHOD

The composition of the bottom ash used for this project can be found in Table 1. The ash was sieved and ground to a fineness of 2μm in order to be used in the mixes.

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. Bottom Ash Composition

The OPC mortar mixes cast as controls were mixed using a OPC:water:sand ratio of 1:0.5:3 and the pure OPC cement paste mixes had an OPC:water ratio of 1:0.5. The bottom ash replaced OPC by 10% and 40% (w/w). Table 2 shows a typical mortar mix used for the project. The mixes were cast in moulds for 24 hours, covered in wet hessian, and then demoulded and cured in a water bath for up to 28 days.

	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. Typical Mortar Mix

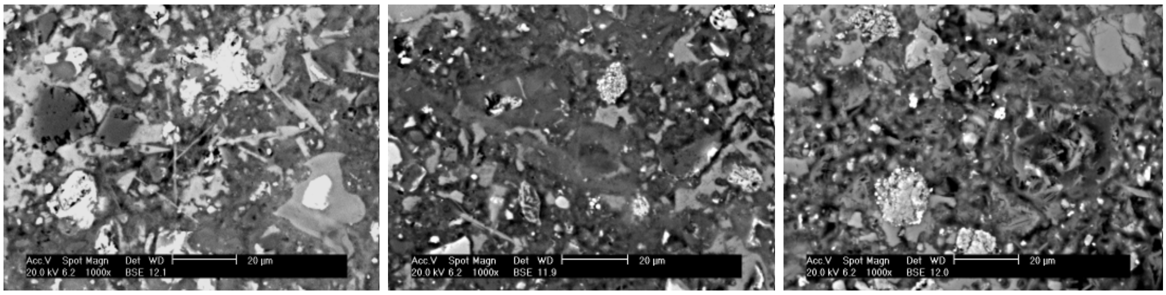
Although the proportions of the different ingredients changed from mix to mix, the water/cement ratio remained the same for any mortar and cement paste mix, excluding the mix prepared to achieve standard consistence. All the tests performed were tested using the British Standard codes wherever possible.

RESULTS AND DISCUSSION

Scanning Electron Microscopy (SEM)

SEM images were taken on cement paste mixes prepared to see the effects on the internal structure with the samples having their hydration stopped after 28 days and then cut and polished to expose a smooth surface for examination. These images are presented in Figure 1 and show a complicated, heterogeneous microstructure with clumps of bottom ash appearing as bright regions in Figures 1b and 1c.

The majority of the bottom ash particles were angular and very small – less than 5μm in diameter – with some being larger. Their replacement of OPC resulted in an increase in the effective water/cement ratio and hence an increase in the porosity of the structure. These pores are seen in Figure 1 as the dark regions between the hydrated material.



(a) (b) (c)

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

WORKABILITY

The effects on workability have been measured using the flow table test in accordance to BS 4551-1:1998[4]. The results are summarised in Table 3 below, D1 and D2 being the diameter of the spread measured at normal angles.

	OPC	OPC+10%BA	OPC+40%BA
D1	190 mm	168 mm	138 mm
D2	190 mm	165 mm	134 mm
average	190 mm	166.5 mm	136 mm

Table 3. Flow Table Test Results

The replacement of OPC with bottom ash led to an increase in water/cement ratio (Table 2) which increases workability, and hence increases the flow. However the addition of bottom ash in the mix leads to a decrease in flow, most likely due to the nature of the bottom ash. The very small particles and their angular surfaces increase the specific surface area of the mix, resulting in a higher water demand to satisfy the same workability.

STRENGTH

Mortar Strength was measured in accordance with BS 4550-3.4:1978[5], the result of which can be found in Figure 2. The only minor difference in testing was that instead of testing 70.7mm cubes as the codes stated, 50mm cubes were used. This was due to mould availability and to limit the amount of bottom ash due to its harmful nature (presence of heavy metals). The standard does allow for a variation in cube size. At low levels of replacement (10%), very little difference was observed. At 40% replacement, the strength significantly dropped by 48% at 28 days. When normalised to the OPC content, at 10% replacement it can be seen that the reduction in strength is due to the loss of OPC (the change in water/cement ratio is negligible). At higher levels of replacement, the difference in strength is not only due to the reduced quantity of cement, but also because of the large increase in water/cement ratio, resulting in a more porous structure as observed in the SEM images.

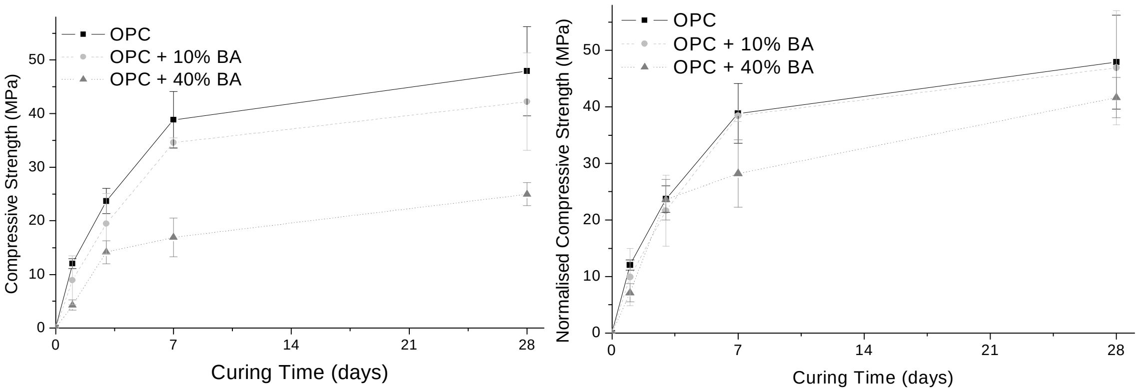


Figure 2. Ultimate Cube Strength Evolution

CREEP AND SHRINKAGE

The effects of bottom ash on creep and shrinkage were investigated. These measurements were performed on 75mm diameter and 250mm long cylinders. Although a typical test lasts 100 days, strain was only measured for 28 days due to time constraints. The total strain measured by the end of the tests are summarised in the table below.

	Creep Strain	Shrinkage Strain	Total Strain
OPC	1.72×10^{-4}	2.83×10^{-4}	4.55×10^{-4}
OPC+10%BA	2.90×10^{-4}	5.33×10^{-4}	8.23×10^{-4}
OPC+40%BA	5.69×10^{-4}	6.28×10^{-4}	12×10^{-4}

Table 4. Creep and Shrinkage Results

The replacement of OPC leads to an important increase in the strain. The total strain is almost tripled when 40% of the OPC is replaced. The reason for this is because the increase in the water/cement ratio increases the porosity increase the free water to move around through a more porous matrix and the easier formation of micro cracks.

SETTING TIME

Standard consistence

The setting time is measured on a sample of standard consistence, the mix designs of which are shown in Table 5. These were measured in accordance with BS 4550-3.5:1978[6]. Although less water was needed to achieve the same consistency every time, the water/cement ratio increased as more OPC was replaced by bottom ash, confirming the need to increase water demand to achieve same workability determined from the previous results.

	OPC mix	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

Table 5. Mix Designs Used to Achieve Standard Consistence

Setting time

The setting time was measured with a VICAT penetration test, in accordance with BS 4550-3.6:1978[7]. Figure 3 shows the evolution of the initial setting time, or that moment when the cement paste is considered no longer workable, and Table 6 summarises the results of initial and final setting time—defined as that moment when the paste is fully set. The initial setting time is found when the depth of penetration is equal to 5mm, the results in table found by extrapolation from the graph. The final setting times where found directly from empirical measurements.

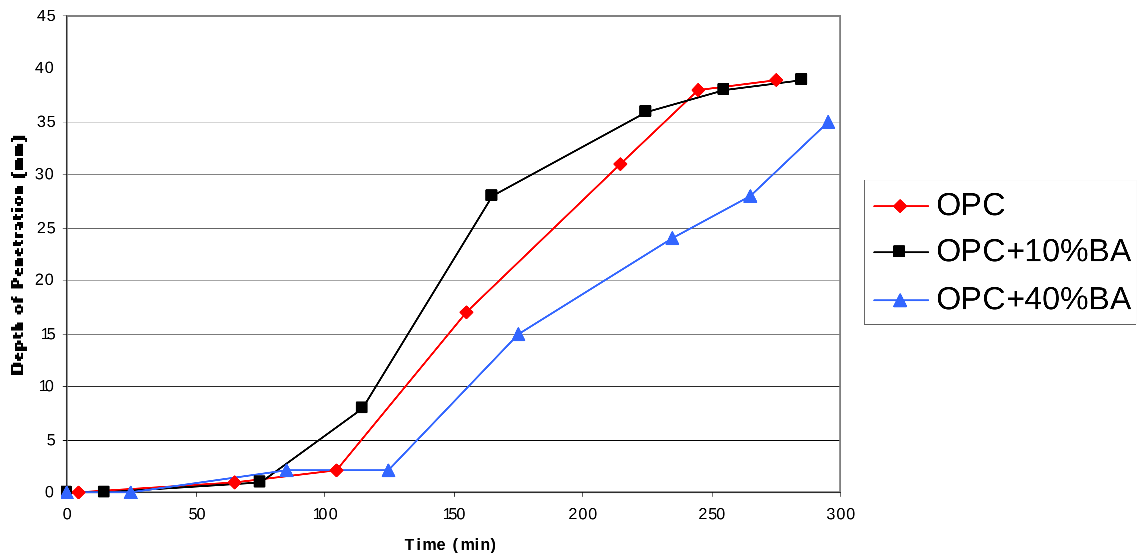


Figure 3. Evolution of Depth of Penetration while Determining the Initial Setting Time

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

Table 6. Setting Time Results

At 10% replacement of OPC, the setting time is increased, but retarded when more is replaced. In the first scenario, the addition of bottom ash may provide nucleation sites for hydration and the slight increase in water/cement ratio facilitates the transportation of reactive elements in the mixes. However, at the higher level of replacement, a more important importation of deleterious elements, such as lead and zinc, could slow down the reaction. Olgun *et al*.[8] have found similar results while conducting research on the effects of bottom ash.

CALORIMETRY

The effects on hydration were followed by conduction calorimetry for 72 hours, the results of which are shown in Figure 4. When a little amount of OPC is replaced with bottom ash, the maximum rate of heat evolution is higher and more heat is generated compared to a pure OPC mix. The opposite is observed when more bottom ash is added. This agrees with the setting time results discussed previously. At higher concentration, a bump appears on the curve. This may correspond to the formation of secondary AFt most likely due to a higher concentration of iron and aluminium provided by the bottom ash[9]. This shows that the bottom ash does exhibit limited reactivity. This is confirmed when looking at the total heat evolution. The replacement of 40% of the OPC only decreases of the total heat by evolved 8%. Yan *et al*.[10] investigated the effects of water/cement ratio by calorimetry. They found that an increase in the water/cement ratio increased the total heat of hydration due to a more important flow of water. The slight increase in the water/cement ratio when small quantities of OPC are replaced increased the total heat evolved, but is slowed down when more is replaced due to the incorporation of deleterious materials.

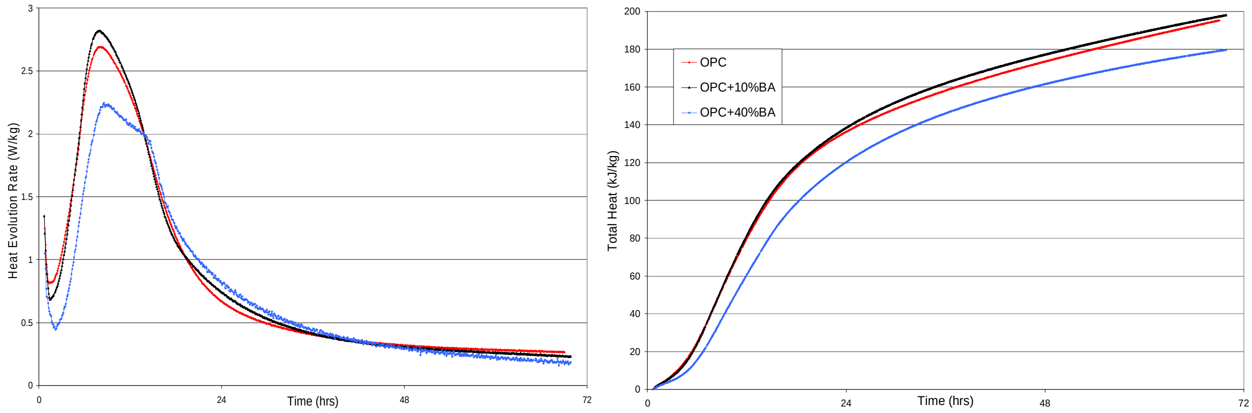


Figure 4. Heat Evolution Rate and Total Heat Evolution

CONCLUSIONS

The research has shown that replacement of OPC with bottom ash affects the properties of mortars. The bottom ash is reactive, but far less so than OPC. At low levels of replacement (10%) performance is not greatly affected, but at high levels (40%) there was a marked decrease in performance.

A primary reason for the decrease in performance at high replacement levels is the effective increased water/cement ratio. This, in turn, leads to an increase in the porosity of the hardened mortar, as shown in the SEM images. The increase in porosity, plus lower OPC contents reduces the UCS of mortar cubes and increases the total amount of creep.

The high specific surface area of the bottom ash particles reduced mix workability. The particles also affected the initial rate of hydration, with setting being accelerated at 10% replacement, but retarded at 40% replacement. This was confirmed by the conduction calorimetry performed, which also revealed that the bottom ash was not inert.

Bottom ash may replace a low amount of OPC in civil engineering purposes in the future, although more research will have to be conducted beforehand to assess its affect on durability.

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