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Performance of masonry blocks containing different proportions of incinator bottom ash

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ABSTRACT

This paper presents the results from an experimental suite of tests as a trial to assess the structural and material performance of masonry blocks with different proportions of incinerator bottom as (IBA) as a fine aggregate replacement. The tests undertaken include compressive and flexural strengths, water absorption and density.
Research into the use of waste by-products in construction materials has been increasing over the past 20 years. IBA produced in an Irish waste incinerator facility is currently landfilled following pre-treatment. This project assesses the suitability of this IBA to replace 0, 10, 20, 30, 50, 75 or 100% of natural fine aggregates in masonry blocks (100 mm high × 215 mm wide × 440 mm long) with a design strength of 7 N. Structural tests included compressive and tensile strength, density and water absorption in accordance with ASTM C140.
The results indicate that bottom ash replacement levels below 20% provide adequate compression and tensile strengths with density and absorption also within satisfactory levels.

1. Introduction

Irish aggregate demand is forecast to increase by 10 million tonnes per year to 2021 with the worldwide demand expected to rise by 5.2% annually to over 56 billion metric tons over the same time period [13]. The land-based sources of primary aggregates are hard rock quarries, sand & gravel pits with future supply from existing pits, quarries, extensions to same and new 'greenfield' sites. A preliminary assessment of the land take required to meet this forecasted demand is approximately 2400 ha for sand & gravel and 1730 ha for crushed rock representing 0.06% of Ireland's total land surface.

Incinerator Bottom Ash (IBA) is one of the main by-products of Municipal Solid Waste Incineration (MSWI). It is part of the non-combustible residue of combustion in a furnace and contains ferrous and non-ferrous metals. Over 60 million tonnes of municipal solid waste is incinerated in the European Union annually with over 20 million tonnes of bottom ash produced. Due to the volume of European bottom ash recycled and used in construction materials, utilization legislation across Europe is being tightened. Denmark, France, Germany and the Netherlands have implemented national legislation to regulate utilization of MSWI bottom ash [14]. Denmark and the Netherlands have set utilization targets of 85% and 100% respectively which are based on leaching criteria. The management of MSWI bottom ash across Europe is focussed on marketing and utilization with similar disposal standards. Standardised test methods are also required to ensure that environmental considerations are similar across the Union [14]. Due to the many practical and administrative barriers identified in a 2006 bottom ash waste management report [14] including differing tax politics, operational guidelines, utilization, disposal and exports, finding a sustainable use of this by-product in construction materials could offer many potential applications whilst not adversely affecting the performance of the structures it is integrated into.

MSWI generation in Ireland between 2001 and 2010 peaked in 2006 at 794 kg/capita but reduced to 636 kg/capita in 2010 as a result of the economic recession [20]. The majority of MSWI generated in Ireland continues to end in landfill. However, the volume landfilled reduced significantly during the first decade of the millennium falling from 77% in 2001 to 53% in 2010. The MSWI that supplied the bottom ash for this study opened in August 2011 and generates 18 MW of electricity which can provide power to over 22,000 homes.

This paper presents the use of bottom ash in masonry blocks to reduce the volume going to landfill as a fine aggregate replacement. The results here show that, up to a point, including IBA has minimal effect in terms of compressive and flexural strength and water absorption while reducing the self-weight.

2. Bottom ash as a construction material

IBA is the non-combustible fraction of the waste charged to the furnace that forms a residue which remains on the grate at the end of the combustion cycle. It is produced from the MSWI raw ash after it has cooled and is generated at a rate of approximately 200–250 kg/t of waste incinerated. The IBA stream consists primarily of glass, ceramics,

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ferrous and nonferrous metals as well as some unburnt material. These contaminants are removed during the production process and the ash is aged or weathered with rigorous quality control procedures in place to ensure it presents no threat to the environment.

IBA is a coarse, angular shaped material with a porous surface texture containing small amounts of unburnt organic material and metals. It is composed of alumina, silica and iron with small quantities of calcium, magnesium and sulphate. Grain size generally ranges from fine sand to gravel and has similar physical properties to fly ash but typically contains greater quantities of carbon [15].

The presence of a relatively high salt content and trace metal concentrations including lead, cadmium and zinc in municipal waste combustor ash (compared with conventional aggregate materials) has raised concerns in recent years regarding the environmental acceptability of using it as an aggregate substitute. The presence of calcium and other salts in relatively high concentrations in MSWI combustor ash makes it susceptible to hydration and/or cementitious reactions (particularly in combined ash which contains unreacted lime) and subsequent swelling. The presence of free aluminium in the ash when combined with water can also result in the formation of hydrogen gas. In addition, the high salt content also suggests that ash could be corrosive if placed in contact with metal structures and that it would likely interfere with curing and strength development if used in Portland cement concrete [14].

Therefore, the most applicable use of bottom ash is in construction elements which are not subject to embedded steel corrosion, or other internal processes that detrimentally affect the performance of the structure. Further research into the processing and removal of metals and the material variability is needed.

2.1. Bottom ash usage

According to the Confederation of European Waste-to-Energy Plants [11], the preference for utilising bottom ash is to replace sand and gravel. In many countries there is an increasing shortage of suitable natural aggregate and lack of available landfill space. In Europe, the primary uses of IBA are in road construction as a capping layer on landfill sites, in noise barriers and as an aggregate in asphalt and concrete not in direct contact with groundwater. The A12 motorway at De Meem in the Netherlands for instance consists entirely of waste-to-energy bottom ash [11].

2.2. Bottom ash as an aggregate

IBA has high shear strength with low compressibility which makes it ideal for use in the construction of dam and other civil engineering applications. Bottom ash also exhibits a reasonably high permeability and grain size distribution which allows it to be used in direct contact with impervious materials and can be used as a replacement for aggregate or for other engineering applications where sand, gravel and crushed stone are used [15]. The majority of MSWI bottom ash that is used as an aggregate in concrete has a particle size range of 2–40 mm [17]. Recycling these wastes as construction material is permitted provided that the management of resources is considered beforehand. Recycling in this way was initially required to decrease heavy metals leaching in landfills and into the environment [17].

Table 1
Summary of the masonry and concrete cast.

Masonry blocks (440 × 215 × 100 mm thick)	
Mix ID	Description
PM1	CEM I
BA10	CEM I + 10% IBA
BA10	CEM I + 20% IBA
BA10	CEM I + 30% IBA
BA10	CEM I + 50% IBA
BA10	CEM I + 75% IBA
BA10	CEM I + 100% IBA

Table 2
Mix ingredients — masonry.

Mix ID	Mass of ingredients (kg/m^3)							
	CEM I	Water	IBA	14 mm	6 mm	Dust	FA	SP
PM1	115	48	0	313	771	398	205	0.8%
BA10	115	48	20.5	313	771	398	184.5	0.8%
BA10	115	48	41	313	771	398	164	0.8%
BA10	115	48	61.5	313	771	398	143.5	0.8%
BA10	115	48	102.5	313	771	398	102.5	0.8%
BA10	115	48	153.8	313	771	398	21.2	0.8%
BA10	115	48	205	313	771	398	0	0.8%

FA = fine aggregate; SP = super-plasticiser per weight of cement (%).

MSWI ash has been generally used as a substitute for valuable primary aggregate resources for the past 20 years in Europe for the construction of roads and embankments. In some countries, including the Netherlands, practically all IBA ashes are reused. In the UK, an increasing supply of bottom ash has led to it becoming a secondary aggregate due to its cost and environmental benefits [12].

3. Experimental programme

3.1. Mix proportions

The masonry and concrete cast for this study included one control mix incorporating only CEM I cement and a number of other mixes containing IBA with sand replacements of 10, 20, 30, 50, 75 and 100%. A summary of the masonry cast is reported in Table 1. The masonry mixes all had a fixed water to cement (w/c) ratio of 0.42 and a cementitious material content of 115 kg/m^3. The mix proportions for the masonry blocks are summarised in Table 2.

3.2. Materials

CEM I cement complying with [5] was used as the cementitious material. Both the fine and coarse aggregates were obtained from local sources in Ireland. The fine aggregate used was medium graded sand and the coarse aggregate was crushed limestone with a maximum size of 20 mm. The chemical composition of the cements used and physical properties of the aggregates in terms of the impact [8] and crushing [9] value and 10% fines [10] are given in Tables 3 and 4 respectively.

The dry 0–19 mm IBA was passed through a 5 mm grate and what was retained on a 2.36 mm sieve was used as the fine aggregate (sand) replacement.

3.3. Preparation of samples

3.3.1. Masonry blocks

The masonry blocks were manufactured using a pan mixer. For each mix in Tables 1, 6 blocks (440 × 215 × 100 mm thick) were cast to determine the structural properties including the compressive and flexural strength (at 28 days), absorption and density. Each mix had a volume of 0.068 m^3 including 20% for wastage.

Table 3
CEM I chemical composition (unignited format).

Chemical	Proportion (%)
SiO_2	19.33
$ALSO_3$	4.91
Fe_2O_3	2.98
CaO	63.59
SO_3	3.10
Na_2O	0.59
F.CaO	2.39
LOI	2.27
Insoluble residue	0.54

Table 4
Aggregate physical properties.

Aggregate/property	Aggregate impact	Aggregate crushing	10% fines
Bottom ash	69.6%	55.9%	93.4 kN
6 mm aggregate	23.1%	35.7%	142 kN
10 mm aggregate	16.6%	12.9%	269 kN
14 mm aggregate	10.3%	16.3%	325 kN
20 mm aggregate	7.62%	6.4%	352 kN

After mixing, the concrete was poured in 50 mm thick layers into the stainless steel moulds (Fig. 1) with each layer vibrated on a vibrating table for a time until no more air bubbles were visible on the surface. Curing was provided by placing a polythene sheet over the specimens for 24 h to trap moisture that evaporates from the surface. Following demoulding, the samples were placed in water in a curing tank at 20 ($\pm$2)$^{\circ}$C until testing.

3.4. Tests carried out

3.4.1. Density

The density (kg/m^3) of each block was calculated by determining the weight (kg) and volume (m^3) by measuring the length, width and thickness.

3.4.2. Water absorption

The water absorption for each masonry block was carried out in accordance with ASTM C140-11a [3]). They were first dried in an oven at 105 °C for 24 h to obtain the dry weights (W_d, kg). The blocks were then placed into a water bath for a further 24 h and the saturated weights obtained (W_s, kg). The percentage water absorption (W_a) was determined using Eq. (1) where V is the volume of the block (m^3). The maximum allowable water absorption percentage for masonry units of this size and density is 12%, in accordance with ASTM C90-11b [4]).

$$W_a = \frac{W_s - W_d}{V} \tag{1}$$

3.4.3. Compressive strength

The compressive strength for the masonry blocks was determined by crushing three samples per mix at 28 days in accordance with ASTM C140-11a [3]). The blocks were placed into a compressive testing apparatus with two 100 × 215 × 10 mm thick plates placed above and below each sample to distribute the load evenly. Fig. 2 shows a cast block before and during compression strength testing.

3.4.4. Flexural strength

The flexural strength for the masonry was carried out in accordance with [7]. The blocks were positioned on their flat into a flexural beam apparatus (Fig. 3) and subject to a 4-point loading arrangement with

Fig. 1. Stainless steel moulds used to cast the masonry blocks.

(a) (b)

Fig. 2. Masonry block (a) cast and (b) ready for compression testing.

Fig. 3. Masonry block undergoing flexural loading.

the maximum load recorded. From this, Eq. (2) was used to determine the flexural strength (Fc, N/mm^2) where F is the maximum load (N), l is the distance between supports (mm) and d_1 and d_2 are the cross-sectional dimensions.

$$F_c = \frac{3Fl}{4d_1\left(d_2^2\right)} \quad (2)$$

4. Experimental results

4.1. Density

Table 5 and Fig. 4 shows the variation in the average densities of the masonry blocks with the addition of IBA. As the volume amount of bottom ash increases, there is a corresponding decrease in unit density.

4.2. Water absorption

Table 5 and Fig. 5 show the average water absorption results from the masonry blocks. As may be seen, there is a steady increase in water absorption with bottom ash content. According to ASTM C90-11b [4]), the acceptable value of water absorption in masonry blocks is 12%. The results here show that the absorption of the 20% replacement masonry block (11.2%) satisfies this recommendation. The remaining blocks have absorption rates higher than this recommendation which was confirmed previously by Abeykoon et al. [1]).

Table 5
Complete results for all tests.

Compressive strength (MPa)							
Block no.	Plain	10% BA	20% BA	30% BA	50% BA	75% BA	100% BA
1	10.9	8.1	7.4	6.8	6.21	4.8	4.3
2	10.7	7.6	7.3	6.5	5.62	5.5	4.2
3	10.5	7.8	7.4	6.7	5.8	4.8	3.5
Average	10.7	7.8	7.4	6.7	5.9	5.0	4.0
Flexural strength (MPa)							
Block no.	Plain	10% BA	20% BA	30% BA	50% BA	75% BA	100% BA
1	2.2	1.73	1.58	1.52	1.49	1.37	0.98
2	2.38	1.89	1.63	1.49	1.46	1.25	1.1
3	2.2	1.92	1.66	1.42	1.37	1.2	0.98
Average	2.3	1.8	1.6	1.5	1.4	1.3	1.0
Density (kg/m^3)							
Block no.	Plain	10% BA	20% BA	30% BA	50% BA	75% BA	100% BA
1	2193	2185	2165	2142	2108	1998	1998
2	2204	2164	2145	2106	2105	2034	2014
3	2214	2193	2093	2135	2091	2019	1966
4	2204	2194	2156	2141	2106	2125	1987
5	2183	2182	2114	2101	2098	2019	1977
6	2250	2193	2093	2086	2089	1987	2110
Average	2214	2185	2128	2119	2099	2030	2009
Absorption (%))							
	Plain	10% BA	20% BA	30% BA	50% BA	75% BA	100% BA
Result	7.0	9.4	11.2	14.6	16.4	18.3	20.4

Fig. 4. Variation in masonry density with the additional of bottom ash.

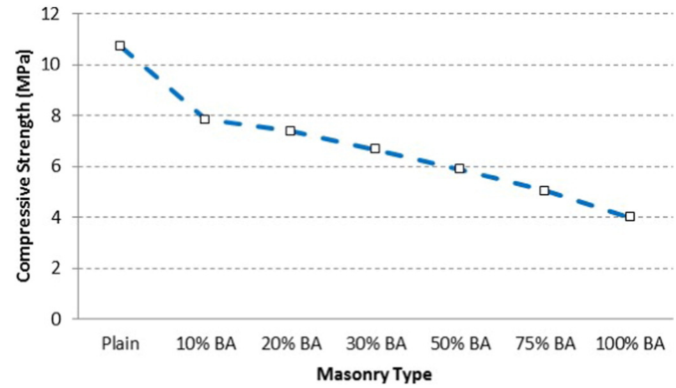

Fig. 6. Compressive strength results.

Bottom ash contains a greater amount of finer particles than sand, which leads to more water needed to cover the surface. The surface of bottom ash has an angular particle shape, which increases the friction between particles. The surface of bottom ash is also surrounded with dust which has been found to absorb more water [19]. The bottom ash used for this study was quite water absorbent as it didn't undergo any pre-saturation before mixing. The water absorbency of bottom ash has also been highlighted previously [14]. Over absorption of water in masonry has also been found to affect the strength gain early on as insufficient moisture is available for full hydration to occur. Remya et al. [16]) also found that water absorption increased with improved capillary pores connectivity with the addition of bottom ash.

A study undertaken by Abeykoon et al. [1]) on incorporating bottom ash as fine aggregate in masonry blocks found that the water absorption increased for replacement levels of 0–30% and the masonry became more absorbent due to the increased porosity and the dry particles resulting from waste combustion.

4.3. Compressive strength

Table 5 and Fig. 6 show the average compressive strength results from the study. As may be seen, the highest strength was obtained in the plain masonry blocks. As the percentages of bottom ash increased, there is a steady reduction in strength. Only the 10 and 20% replacement levels had compressive strengths less than the design strength, namely 7 N.

The loss in strength can be due to three factors. Firstly, bottom ash tends to absorbs water making it unavailable for cement hydration. As masonry must limit its water absorption to 12%, the 20% bottom ash replacement level would therefore be acceptable as it satisfies both. Secondly, fine aggregates reduce the porosity of the masonry which improves compressive strengths. By replacing natural aggregates with bottom ash, the porosity will be increased and a loss in strength is expected. Lastly, bottom ash has little or no pozzolanic effect and does not contribute to strength development. Calorimetric measurements have demonstrated that cement hydration is retarded when bottom ash fines are used [19]. Abeykoon et al. [1]) also found the strength of masonry blocks decreased with increasing bottom ash quantities and the optimum replacement level of 20% was considered ideal.

4.4. Flexural strength

Table 5 and Fig. 7 show the average flexural strengths of the masonry blocks with a similar trend as the compressive strength. However, the difference in flexural strengths between 10 and 100% replacement is marginal and much less than the compressive strengths. This is consistent with previous work by Aggarwall et al. [2]) who found negligible differences in flexural strengths of concrete bottom ash. Sandhya and Reshma [18]) and Remya et al. [16]) both found in their studies that bottom ash inclusion in concrete results in poor interlocking between aggregates and reduced the flexural strength. Remya et al. [16]) postulated that cracks caused by flexural loading propagate easier through bottom ash particles as compared with natural fine aggregates.

5. Conclusions

On the basis of the various investigations carried out to assess the effect of IBA as a fine aggregate replacement in masonry blocks IBA fine aggregate replacements of ≤20% have shown to maintain compressive strength while complying with the 12% water absorption criteria in structural masonry. This also produces a slightly lighter block than

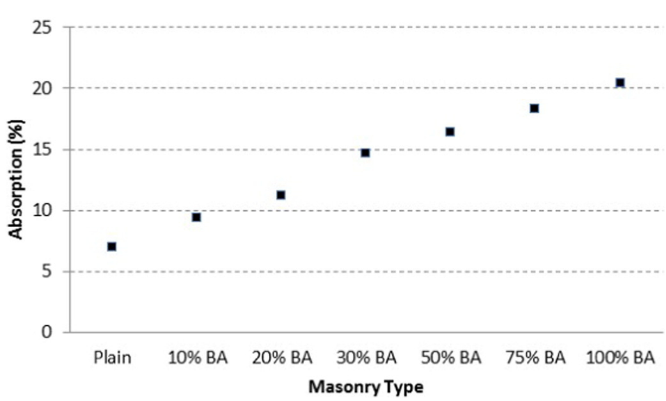

Fig. 5. Water absorption results.

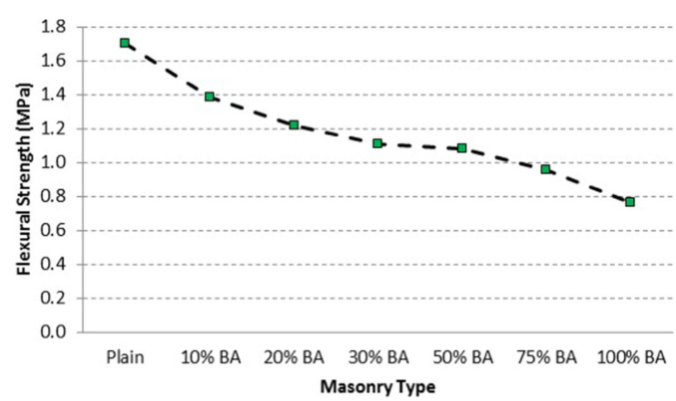

Fig. 7. Flexural strength results.

plain masonry. While the findings show the potential of IBA as a fine aggregate replacement in masonry elements and a possible way of reducing natural aggregate usages, more research in this area is required.

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