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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