

Production of lightweight aggregate from incinerator bottom ash and pulverised fuel ash

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Abstract

Waste incineration is increasingly considered a leading alternative to landfill in many countries due to limited availability of landfill sites and potential adverse environmental effects associated with waste disposal. Incinerator bottom ash (IBA) residues are generated at a rate of approximately 800 kilotonnes per year in the UK and the majority is currently landfilled. The production of lightweight aggregate by sintering mixes of municipal solid waste IBA and pulverised fuel ash (PFA) represents a potentially attractive reuse application for these high-volume waste materials. PFA has been added to IBA to control the sintering behaviour. The effect of adding a carbonaceous material that decomposes during firing to produce controlled levels of porosity has been investigated. Waste activated carbon has been used as a pore former in pellets containing significant quantities of IBA. Two lightweight aggregates were manufactured, a carbon-free and a carbon-containing aggregate, and were characterised in terms of physical, mechanical, mineralogical and microstructural properties. The IBA-derived aggregate performance was assessed in comparison with commercial synthetic aggregate (Lytag) and the results confirmed the feasibility of the production of lightweight aggregate using significant concentrations of the high-volume combustion bottom ashes.

Keywords: waste reuse, incinerator bottom ash, pulverised fuel ash, resource conservation, aggregate.



1 Introduction

In the past few decades, the rapid process of industrialisation and urbanisation has increased the generation of waste materials at tremendous rates, and landfills are filling up faster than the exploration of new sites. Incineration is increasingly considered a viable alternative to landfill for the disposal of municipal solid waste (MSW) due to increasing restrictions on landfill. Although incineration reduces the volume of municipal waste by up to 80-90%, Energy from Waste (EfW) plants still produce considerable amounts of incinerator bottom ash most of which is currently disposed of in landfill or used in low-grade civil engineering applications.

IBA is a heterogeneous mix of ceramic materials such as brick, stone, glass, ferrous and non-ferrous metals and other non-combustible and residual organic matter [1,2,3]. The current relatively low level of IBA reuse combined with the potentially large amounts that are likely to be produced in the future makes the development of new applications for this material an important research area.

PFA is the residue produced from the combustion of finely ground coal at power stations. It is used in concrete, road construction, soil stabilisation and LWA production, although large amounts remain in ash repositories, Clarke [4].

One of the most attractive reuse applications for mineral wastes and combustion ashes is the manufacture of lightweight aggregate (LWA). Processing IBA combined with PFA to produce lightweight pellets suitable for potential use as LWA would contribute towards solving the problems associated with the disposal of these materials, while providing an alternative to depleting natural aggregate resources. An important requirement is that the processing must produce environmentally benign products that have no adverse implications for the environment and public health. Lightweight aggregates have been manufactured by sintering ashes from the incineration of PFA or IBA [5, 6, 7] and a number of other waste materials [8, 9].

Previous work has investigated the effect of sintering on the physical, mineralogical, microstructural and leaching properties of IBA and demonstrated that sintering the fine fraction (<8mm) of IBA can produce dense ceramics with maximum densities of 2.6g/cm³ and significantly reduced availability of most metals under all pH environments due to encapsulation and incorporation into glassy and crystalline phases, Cheeseman *et al* [10]. However, sintering occurred over a relatively narrow temperature range before sample bloating and softening resulted in a reduction in density, Bethanis *et al* [11].

The aim of this work was to investigate the potential of producing porous ceramic materials for use as lightweight aggregates by processing mixes of IBA and PFA and assess their properties in comparison with commercially available Lytag aggregates. The incorporation of a combustible organic material that “burns out” during firing, leaving voids in the resulting body is a common approach to fabricate porous materials. The effect of introducing a carbonaceous material into mineral waste to control porosity and produce low-density ceramic materials has been investigated. In this work waste activated carbon has been used as a pore forming additive in IBA with PFA mixes.



2 Experimental procedure

2.1 Materials

IBA was obtained from a major ash processing plant in SE England where it had been weathered for between six to eight weeks. The majority of the ferrous and non-ferrous metals were already removed and the ash with a particle size of <8mm was selected for use in these experiments. This size fraction represents approximately 45% by mass of the total weathered ash and was used because commercially viable outlets for this material have not so far been developed.

Low-lime pulverised fuel ash was obtained from Drax coal-fired power station at Selby, UK. Drax Power station is the largest coal-fired power station in Western Europe, and consists of six 660MW coal-fired generating units, which are fed with coal ground to a fine dust. The total ash produced accounts for approximately 1.3-1.4 million tonnes per year. Waste activated carbon was collected from Grafham Carbons in Tipton, West Midlands.

2.2 Chemical and mineralogical characterisation

In order to minimise the effect of sample inhomogeneities in IBA the chemical properties of the material were assessed after milling. The elemental composition of dried milled IBA and as-received PFA were determined by digestion using lithium metaborate and tetraborate flux fusion, Ingamells [12]. Digests were analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Crystalline phases present in milled IBA and as-received PFA were analysed by X-ray diffraction (XRD) (Phillips PW1830) using Cu $K\alpha$ radiation at an accelerating voltage of 40 kV.

2.3 Production of IBA/PFA pellets containing carbon

500g batches of 40/60 (IBA/PFA) mixes containing 0, 2, 7, 10 and 12% by weight waste activated carbon were wet-milled for 8 hours in a 3 litre polypropylene mill containing high-density alumina milling media rotating at approximately 50rpm. The milled slurries were passed through a 355 μ m sieves to remove oversize material prior to de-watering by pressure filtration using a stainless steel extraction vessel (Whatman GF/C filter paper). The filter cakes formed were oven-dried overnight at 105°C and ground in a pestle and mortar to produce a fine powder to pass through a 710 μ m mesh sieve.

The dried milled powders were mixed with increasing amount of water until the consistency of the clay-like material formed allowed pelletisation in a revolving drum. The pellets retained by a 4mm sieve and passing through a 10mm sieve were used for sintering. The aggregates were coated with PFA to produce a skin on the pellet surface that would aid separation of individual pellets and create a thin dense outer skin on the fired pellet. The aggregates were then oven-dried overnight at 105°C before sintering in a rotary furnace between 1040 and 1140°C with 20°C temperature increments.



2.4 Characterisation of sintered pellets

The density of sintered pellets was determined using Archimedes' method and the water absorption capacity determined from the weight increase of "surface dry" samples after immersion in water for 24 hours. Tests on bulk density of aggregates were conducted according to B.S 3797 [13] and the Aggregate Crushing Value test according to B.S 812 [14]. Corresponding properties of Lytag aggregates were also determined using identical test techniques to those used for sintered IBA/PFA pellets.

The ash-derived aggregates were crushed and ground to $<150\mu\text{m}$ to determine the crystalline phases present by XRD. These were also sectioned, polished using $1\mu\text{m}$ diamond paste and examined using scanning electron microscopy (SEM-Phillips XL40).

3 Results

3.1 Materials characterisation

The chemical compositions of milled IBA and as-received PFA are given in Table 1. Milled IBA contained high levels of SiO_2 and CaO , with lower concentrations of Al_2O_3 and Fe_2O_3 , also found in other IBA characterisation studies. SiO_2 , Al_2O_3 and Fe_2O_3 were the major oxides in the as-received PFA. However, the CaO content was much lower ($<2\%$) than in the milled IBA and based on this analysis data the Drax PFA could be classified as a type F fly ash. Other elements present at relatively high concentrations included Na, K, Mg, P, and Ti.

Analysis of XRD data for the milled IBA and as-received PFA showed that the main crystalline phases present in milled IBA were quartz (SiO_2) and calcite (CaCO_3), together with smaller amounts of gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$) and some hematite (Fe_2O_3). Major crystalline phases present in PFA were quartz and mullite ($\text{Al}_6\text{Si}_2\text{O}_{13}$), with smaller amounts of hematite and possibly some anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$). These are in general agreement with mineralogy reported previously in IBA and PFA [1, 3, 15, 16].

Table 1: Chemical composition of milled IBA and as-received PFA.

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2
IBA	41.2	11.9	6.7	18.5	1.9	2.7	0.9	1.4	1.1
PFA	51.6	27.2	11.1	1.4	1.5	1.4	3.8	0.4	0.9

3.2 Effect of carbon on properties of sintered pellets

The effect of carbon on the density and water absorption of 40/60 (IBA/PFA) pellets is given in Table 2. Carbon addition has a significant effect on reducing the densities of fired pellets but this is reduced with increasing firing temperature, especially above 1100°C . At 1080°C , increasing the carbon concentrations to 7, 10 and 12% resulted in 11, 12 and 15% density reductions respectively. All carbon-containing pellets fired at this temperature achieved



significantly lower densities than Lytag aggregates (1.48g/cm^3). Water absorption significantly increased with carbon addition although the extent of increase was reduced in higher temperatures.

Table 2: Effect of carbon on density and water absorption of sintered 40/60 (IBA/PFA) pellets.

Temp. (°C)	Density (g/cm^3)					Water absorption (%)				
	% carbon					% carbon				
	0	2	7	10	12	0	2	7	10	12
1040	1.43	1.36	1.26	1.23	1.20	30.5	32.6	38.9	40.3	42.0
1060	1.48	1.41	1.32	1.29	1.26	28.1	29.8	33.3	35.5	38.7
1080	1.50	1.45	1.34	1.32	1.28	25.3	27.8	31.6	33.7	36.9
1100	1.55	1.50	1.47	1.39	1.36	20.2	22.6	26.3	29.9	30.7
1120	1.58	1.55	1.49	1.43	1.39	19.8	20.6	23.5	25.8	28.0
1140	1.65	1.60	1.57	1.54	1.53	15.2	17.7	18.7	18.8	18.5

3.3 Optimisation and characterisation of ash-derived aggregates

Based on the properties of 40/60 (IBA/PFA) sintered pellets for increasing carbon additions, two IBA/PFA/carbon milled mixes sintered to produce pellets with properties suitable for potential use as lightweight aggregates were selected for production and characterisation. The first selected aggregates (LWA 1) are carbon-free 40/60 (IBA/PFA) pellets fired at 1100°C . The second selected aggregates (LWA 2) are pellets produced from 40/60 (IBA/PFA) containing 7% carbon mix and fired at 1080°C . The average individual and bulk pellet properties of the optimised ash-derived aggregates are summarised in Table 3, together with the properties of commercial Lytag aggregate.

Table 3: Properties of ash-derived and commercial aggregates.

LWA description	Individual pellet properties		Bulk pellet properties	
	Density (g/cm^3)	Water absorption (%)	Density (g/cm^3)	ACV (%)
LWA 1	1.55	20.3	0.89	19.9
LWA 2	1.32	31.9	0.79	45.2
Lytag	1.48	16.0	0.85	34.2

Pellets fired at 1100°C (LWA 1) showed comparable individual and bulk pellet densities to Lytag aggregates (relative density around 1.5g/cm^3 , loose bulk density between 0.8 and 0.9g/cm^3). However, although LWA 1 had higher water absorptions, when loaded in compression they resisted higher stresses having a lower ACV than Lytag. Carbon-containing pellets (LWA 2) achieved significantly lower densities than LWA 1 and Lytag and had considerably high water absorptions due to carbon decomposition, which is also responsible for the higher ACV. LWA 1 achieved density of 1.55g/cm^3 and had 20% water absorption and LWA 2 showed density of 1.32g/cm^3 and 32% water absorption. The ash-derived aggregates are shown in Figure 1.





Figure 1: Sintered ash-derived aggregates a) LWA 1 and, b) LWA 2.

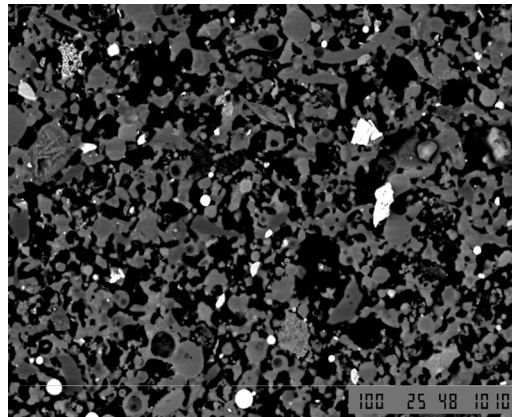
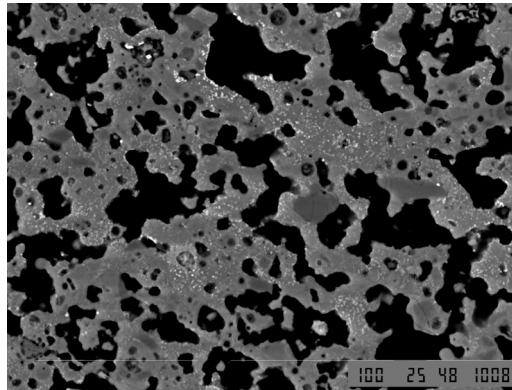


Figure 2: SEM micrographs of polished surfaces of a) LWA 1 and, b) LWA 2.

3.4 Mineralogy and microstructure of ash-derived aggregates

The main crystalline phases present in LWA 1 were sanidine ($(\text{K,Na})(\text{Si}_3\text{Al})\text{O}_8$), anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and magnetite (Fe_3O_4). Sanidine is a common constituent in extrusive igneous rocks, where the rock is rapidly cooled. It is the high temperature form of potassium feldspars or K-spar. Anorthite belongs to the plagioclase feldspars series, which are the commonest rock-forming mineral series [17]. It may form from solid-phase reactions between aluminosilicates, such as mullite, and liberated Ca oxides, carbonates or sulphates during sintering. The principal crystalline phases present in LWA 2 were anorthite, magnetite and quartz, with minor amounts of albite ($(\text{Na,Ca})(\text{Si,Al})_4\text{O}_8$).

Polished surfaces of LWA 1 and LWA 2 are shown in Figure 2(a) and (b) respectively. Both aggregates show high levels of porosity with the addition of carbon causing a significant increase in the level and connectivity of the porosity. It can be seen that in both aggregates there is a significant number of small spherical pores inside the dense glassy phase, due to the incomplete oxidation of carbon in the ash during sintering and the formation of glassy phase. The insufficient oxidation of carbon due to the high heating rate of the pellets also resulted in the development of a greyish-black colouration of the interior-mostly- of the carbon-containing pellets.

4 Discussion

IBA contains significant levels of network modifiers and particularly Ca-containing phases that reduce the melting point of the residual glassy phase in IBA. As a result sintering only occurs over a narrow temperature range before the samples soften and deform, Bethanis *et al* [11]. This makes the use of carbonaceous additives problematic, since the pores created by the thermal decomposition of carbonaceous particles at lower temperatures are effectively filled with glassy phase, resulting in negligible reductions in sintered density.

The incorporation of low lime PFA in IBA intends to increase the concentrations of refractory silicate mineral phases such as mullite and quartz and reduce the overall concentration of CaO. As a result mixes containing reduced amounts of IBA have a higher viscosity glassy phase at a given temperature causing a wider temperature interval between initial sintering and sample melting.

Several preliminary studies on introducing an organic additive in mixes of IBA with PFA (100/0, 80/20, 60/40, 40/60, 20/80 and 0/100 IBA/PFA) showed that the porosity formation effectiveness of the organic material depends on the IBA/PFA ratio and is greatly increased in mixes containing higher amounts of PFA. The IBA/PFA mix containing 40% by mass IBA was considered the optimum mix because it contained significant levels of PFA that would allow porosity formation by the use of a carbonaceous additive while it had wide temperature ranges over which sintered ceramics could be formed. The mix was selected for subsequent processing using waste activated carbon as a pore-forming material. Waste activated carbon was selected because (a) it is a high



carbon content waste material, (b) it is readily available, (b) it is considered a problematic waste in terms of re-use disposal outlets, (c) it is relatively easy to handle and (d) it can be seen as a relatively pure waste for assessing basic aspects of including carbon in the mixes without complication.

Waste activated carbon significantly reduced the densities of 40/60 (IBA/PFA) sintered pellets due to porosity formation from the oxidation of carbon, but this effect was reduced with temperatures increasing above 1100°C. The effect of carbon on the densities of pellets fired at temperatures below 1060°C was considerable due to the fact that these were not completely densified.

Bearing in mind the good performance of commercially available Lytag aggregates in construction, two lightweight aggregates were manufactured from IBA and PFA mixes with properties comparable to Lytag. These aggregates were slightly angular, with a smooth and hard exterior shell and had an intergranular porous microstructure. The carbon-containing aggregates were also characterised by a dark-coloured inner core and a light-coloured zone surrounding the core. The incomplete thermal decomposition of carbonaceous matter is responsible for locally reducing conditions of iron compounds occurring inside the body, which result in the development of black coring in the sintered products [18, 19, 20].

5 Conclusions

1. It is generally feasible to produce porous ceramic materials containing significant proportions of incinerator bottom ashes for potential use as lightweight aggregates. The production process involves wet milling of a mixture of incinerator bottom ash and pulverised fuel ash with or without waste activated carbon, separation of the oversize material, pelletisation in a revolving drum and firing in a rotary furnace at temperatures well below the melting point of the ashes.
2. Two lightweight aggregates with relatively different properties were manufactured by sintering mixes of IBA and PFA (40% by weight IBA and 60% PFA); one with the key properties of density and strength, comparable to commercially available synthetic Lytag aggregates and a lower density aggregate with high water absorption from PFA and IBA mixture containing a carbonaceous material.
3. Sanidine ((K,Na)(Si₃Al)O₈), anorthite (CaAl₂Si₂O₈) and magnetite (Fe₃O₄) were the major crystalline phases present in the carbon-free ash-derived aggregates, while the principal crystalline phases present in the carbon-containing aggregates were anorthite, magnetite and quartz.

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