Value-added utilisation of municipal waste incinerator bottom ash as lightweight aggregate in concrete

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Abstract

Over the last few decades there has been an immense demand for aggregate materials for use in construction. These are currently obtained from primary rock and gravel resources. However, such resources are finite and material extraction is associated with significant environmental costs. In addition, the significant quantities of residues generated by Waste-to-Energy incineration and coal combustion have emphasized the need to find practical reuse applications for these high-volume wastes. These, together with the economic burden of waste disposal and associated adverse environmental impacts, have made it imperative to develop alternative techniques for converting wastes into high-added value products. This paper describes the process used to produce a lightweight aggregate using incinerator bottom ash from municipal solid waste incineration and pulverized fuel ash from coal-fired power plants. The method involves wet milling of the IBA/PFA mixes, pelletisation of the powder mixes and firing in a rotary kiln at high temperatures to produce sintered aggregates. Lightweight aggregates with particle densities between 1.5 and 1.8 g/cm^3, bulk densities between 0.8 and 0.9 g/cm^3 and water absorptions between 16 and 19% by dry weight have been produced. The manufactured lightweight aggregates achieved compressive strengths of approximately 58 N/mm^2 at 28 days when cast in concrete. Corresponding properties of commercial aggregates Lytag and LECA have been determined for comparison. The leaching characteristics of the IBA-derived aggregates were similar to Lytag and showed low heavy metal leachability under non-highly acidic leachate pH conditions. The results confirm the feasibility of producing a lightweight aggregate using 100% by weight combustion ashes.

Keywords: incinerator bottom ash, pulverized fuel ash, clay, Lytag, Leca, aggregate, concrete, leaching.

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1 Introduction

As the majority of aggregates are used as inputs into construction, their demand is driven largely by the level of activity within this industry. The USA for example, shows an annual per capita aggregate demand of close to 9 tonnes; Australia reaches up to 10 tonnes, whilst the UK shows around 4 tonnes. Quarrying is the main industry of aggregate resources in most countries. However, these resources are finite and extracting and processing these materials has the potential to degrade present and future quality of life and environmental health. Quarrying is associated with significant environmental costs that include visual intrusion, noise, dust, loss of amenity and damage to biodiversity.

The treatment and disposal of municipal solid wastes (MSW) is a problem of worldwide concern. Incineration of MSW is a management option achieving up to 80 and 90% reduction in waste mass and volume, respectively. However, the disposal of waste materials even after incineration presents a problem due to the considerable amounts of ash produced. Incinerator bottom ash (IBA) represents approximately 90% by weight of the total ash, and is a burnt-out mixture of slag, ferrous and non-ferrous metal, ceramics, glass, and other non-combustibles and residual organic matter [1, 2]. Because national regulations are reinforcing environmental protection measures against the potential leaching and release of heavy metals from bottom ashes, there is a great interest in finding alternative technological options to convert bottom ashes into an environmentally friendly new marketable material.

The increasing need for power generation has resulted to increasing coal combustion and generation of coal ash residues, the fine fraction of which is pulverized fuel ash (PFA). Although PFA has been used as a cement replacement material in concrete, in aggregate production, in road construction and soil stabilization, large amounts are disposed in ash repositories [3]. This is not ideal due to problems associated with locating new and properly designed landfill sites and concerns over potential long-term adverse environmental effects to ground and underground water resources.

Processing IBA combined with PFA to produce an aggregate, would contribute towards solving the problems associated with the disposal of these wastes while providing an alternative to depleting mineral resources. Researchers have investigated the production of artificial aggregates from a number of waste materials [4-8].

The purpose of this study was to investigate the production of a lightweight aggregate (LWA) using incinerator bottom ash and pulverized fuel ash residues as the raw materials. The production involved the main stages of milling, pelletizing and sintering. The physical properties of the produced lightweight aggregates (LWAs) were assessed in comparison with commercially available aggregates, such as Lytag (sintered PFA) and LECA (expanded clay). The Acid Neutralisation Capacity (ANC) and the release of heavy metals ions as a function of leachate pH have also been studied. Compressive strengths tests were carried out on concrete made with the IBA-derived aggregates, Lytag and LECA.

2 Experimental work

2.1 Materials

IBA was obtained from a major Waste-to-Energy plant situated in south east England that uses conventional mass-burn technology to burn 420,000 tonnes per year of MSW. The IBA sample used in these experiments had been weathered for between 6 and 8 weeks, the ferrous metals removed by magnetic separation and the non-ferrous metals removed using eddy current separators. The remaining ash was sorted into different sizes and the ash fraction with a particle size smaller than 8mm collected. This fraction represents approximately 45% by weight of the total weathered IBA and is the part for which commercially viable reuse applications have so far been relatively difficult to identify. Low-lime PFA was obtained from Drax coal-fired power station near Selby, UK. Drax Power station consists of six 660 MW coal-fired generating units generating approximately 1.3-1.4 million tonnes of ash per annum.

2.2 Chemical characterisation

The compositions of milled IBA and raw PFA were determined by fusion with lithium metaborate and lithium tetraborate flux to 1000°C and acid dissolution [9]. The digests were analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES).

2.3 Production of lightweight aggregates

500 g batches of mixes of 40% by dry weight IBA and 60% by dry weight PFA (referred to as 40/60 IBA/PFA) were wet-milled for 8 hours in a 3 litre polypropylene mill rotating at 50 revolutions/min, using high-density alumina milling media. Milled slurries were passed through a 355 μm sieve to remove oversize, predominantly glassy material, and de-watered 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 to produce a fine powder to pass through a 710 μm mesh sieve. A controlled amount of water was added to milled powder to give a mix consistency that allowed formation of approximately spherical, 4-19 mm diameter pellets. The pellets were coated with PFA to produce a dense surface skin that would aid separation of individual pellets and enhance “green” pellet strength. These were dried overnight at 105°C before sintering in a rotary kiln at 1100°C. The aggregate produced is referred to as LWA-1.

An alternative to the above waste pre-treatment was used in the production of an aggregate, referred to as LWA-2. IBA was oven-dried overnight at 110°C and was then mechanically ground to a size less than 500 μm before being mixed with PFA and clay, at concentrations of 40% by dry weight IBA, 50% by dry weight PFA and 10% by dry weight clay (referred to as 40/50/10 IBA/PFA/clay). The same pelletisation and sintering procedures to LWA-1 were used.

2.4 Physical testing of lightweight aggregates

The apparent, the oven dried and saturated surface dry particle densities and the water absorption of the aggregates were determined according to BS 812 [10]. Tests on loose bulk density were conducted according to BS EN 1097 [11]. Corresponding properties of Lytag (Cemex UK) and LECA (Maxit UK) were determined using identical test techniques to those used for the IBA-derived aggregates.

2.5 Leachate testing of lightweight aggregates

The pH-dependent leaching of heavy metals was determined for the LWA-1 and Lytag using the Acid Neutralization Capacity test [12] combined with leachate analysis by ICP-AES for LWA-1. The aggregates were initially ground to less than 150 μm. A series of 5 g sub-samples were mixed with 30 ml solutions of varying acidity, ranging from distilled water to 2.0 N HNO_3 over 11 equal increments. Samples and leachant were mixed for 48 hours in sealed containers on a rotary extractor, before being centrifuged. The leachate was then extracted by filtering through a 0.45 μm membrane filter and the pH measured before being acidified with 10% volume HNO_3, prior to metal analysis.

2.6 Concrete manufacture and testing

For each aggregate batch, concrete cubes of 100 mm side were manufactured and the compressive strengths at 7, 14 and 28 days were determined to BS EN 12390 [13].

3 Results and discussion

3.1 Material characterisation

The chemical compositions of milled IBA and raw PFA are given in Table 1. Approximately 80% by weight of the milled IBA consisted of silica (SiO_2), alumina (Al_2O_3), iron (Fe_2O_3) and calcium oxides (CaO). The CaO content in PFA was very low (<2%), with SiO_2, Al_2O_3 and Fe_2O_3 being the major components representing 86% by weight of the samples. There are significant differences between IBA and PFA in concentrations of heavy metals of environmental concern. IBA is enriched in Cr, Cu, Pb and especially Zn, with PFA enriched in Ni.

3.2 Characterisation of lightweight aggregates

The IBA-derived aggregates were characterised by a greyish-black coloration of their interior. This is known as black coring and it is caused by the insufficient oxidation of carbon during sintering [14].

Table 1: Chemical composition of milled IBA and raw PFA.

Component	Major elements (wt%)		Minor and trace elements (mg/kg)		
	IBA	*PFA*		*IBA*	*PFA*
SiO_2	41.2	51.6	As	107	109
Al_2O_3	11.9	27.2	Ba	1033	1010
Fe_2O_3	6.7	11.1	Cd	44	4.8
CaO	18.5	1.4	Cr	327	144
MgO	1.9	1.5	Cu	717	212
Na_2O	2.7	1.4	Ni	93	143
K_2O	0.9	3.8	Pb	815	144
P_2O_5	1.4	0.4	Sr	297	288
TiO_2	1.1	0.9	Zn	2500	174

Table 2: Physical properties of aggregates.

Aggregate	Particle density (g/cm^3)		Apparent particle density (g/cm^3)	Water absorption (%)	Bulk density (g/cm^3)
	Oven dried	Saturated surface dry			
LWA-1	1.54	1.79	2.06	16.4	0.865
LWA-2	1.48	1.76	2.05	18.9	0.822
Lytag	0.74	0.85	1.35-1.65	15.0	0.7-0.8
LECA	-	-	0.5	30.0	0.3

The physical properties of LWA-1, LWA-2, Lytag and LECA are summarised in Table 2. LWA-1 and LWA-2 showed higher particle and bulk densities than Lytag but also higher water absorptions. LECA showed low apparent particle and bulk density and high water absorption, which is due to its highly porous microstructure.

3.3 Neutralisation capacity

Figure 1 shows final leachate pH data as a function of acid addition from the ANC test for LWA-1 and Lytag. ANC is primarily controlled by the solubility of calcium minerals and other alkali metals and alkali metal earth elements, and the resulting leachate pH strongly influences contaminant metal solubility and leaching [15]. The aggregates exhibit a rapid decline in pH with the first 0.2 equivalents of acid per kg of solid. This shows the reduced ANC, as a result of sintering, which is responsible for the decomposition of $CaCO_3$ and incorporation of CaO into the glassy and crystalline silicate structures present in the sintered material.

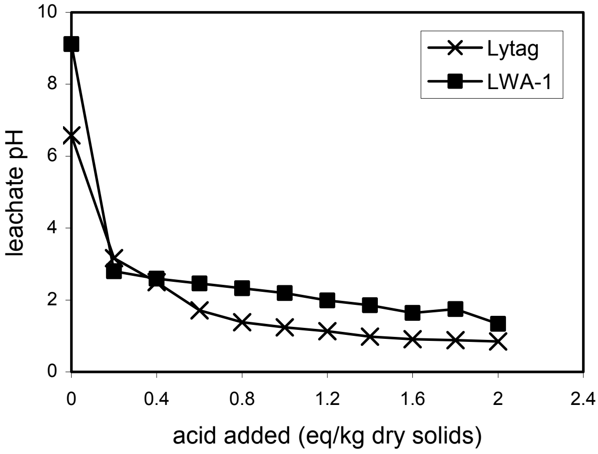

Figure 1: ANC for LWA-1 and Lytag.

3.4 Leachate analysis data

The concentrations of selected heavy metals leached from LWA-1 and Lytag aggregates are plotted as a function of final leachate pH in Figure 2.

The Cr behaviour is very interesting for both aggregates, since there is no significant leaching of Cr even under very aggressive leachate pH conditions. For pH>3 there is practically no Cr leaching. The Cr is very effectively incorporated in silicate or alumino-silicate minerals, or less structured amorphous phases.

No significant Cu is released from the aggregates under alkali leachate conditions. Cu is consistently released from LWA-1 and Lytag for pH<3 reaching values around 60 mg/kg.

The lowest leached Ni concentrations were observed for LWA-1 over the range of leachate pH values examined. For pH< 6 Ni availability increases with acid additions for Lytag to values around 37 mg/kg under highly aggressive environments.

Zinc leachability is extremely low for both aggregates examined under all pH environments. LWA-1 shows higher Zn availability than Lytag for leaching under all pH conditions, but the leachate concentrations were very low.

There is very low leaching of Cd from LWA-1 down to leachate pH values of 3, and this element is effectively not available for leaching from these materials. Maximum Cd release of 2.5 mg/kg is observed from Lytag under highly acidic environments.

There is no detectable Pb leaching from the aggregates for pH>3. For pH<3 Pb becomes available for leaching from LWA-1 reaching values of around 30 mg/kg.

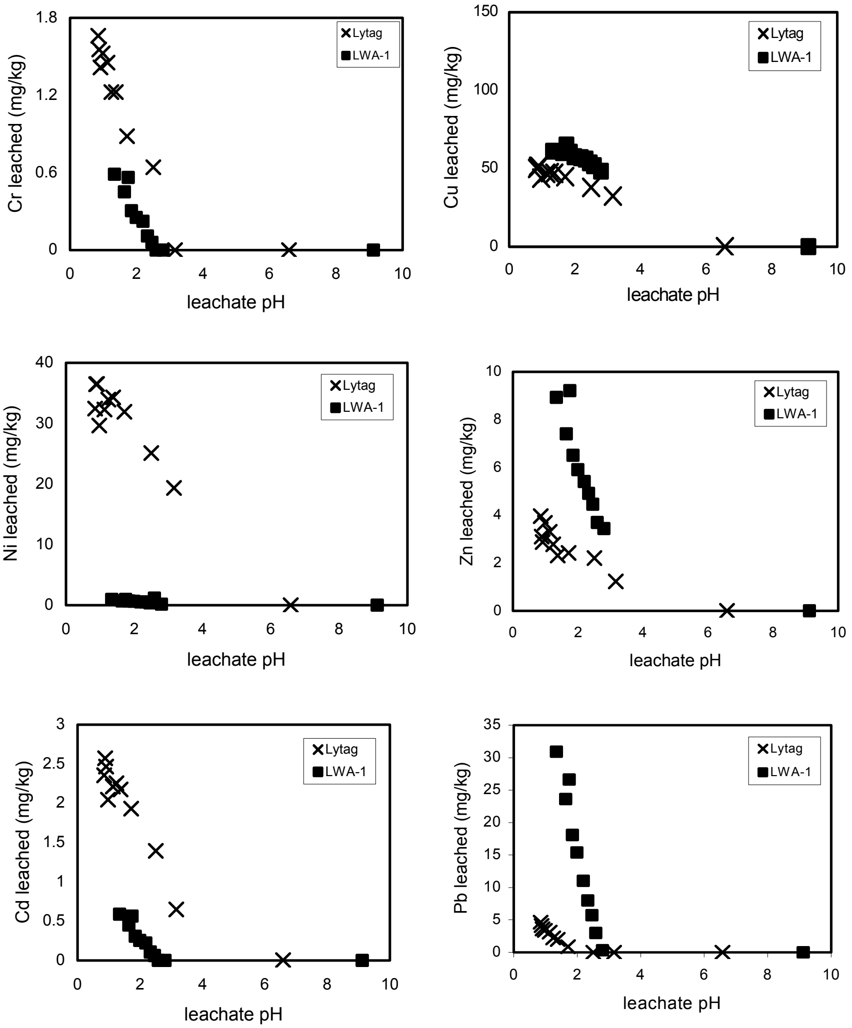

Figure 2: Leaching for Cr, Cu, Ni, Zn, Cd and Pb from LWA-1 and Lytag.

The proportions of these heavy metals in LWA-1 leached under aggressive leachate conditions (leachate pH=3) were derived from the data in Figure 2 and the results are summarised in Table 3. Leaching at pH 3 is considered to represent the highest fraction that is potentially available for leaching, as pH values below this are not normally encountered in the environment.

The most readily available heavy metals from LWA-1 are Cu and Ni, and approximately 10% of the total concentration of these metals is potentially leachable from LWA-1 under aggressive acid conditions. The leachable fraction of all the other heavy metals from LWA-1 is less than 1% of the total metal concentration.

Table 3: Leaching of heavy metals from LWA-1.

Heavy metal	Concentration in LWA-1(*) (mg/kg)	Amount leached from LWA-1 (leachate pH=3)	
		(mg/kg)	% of total
Cr	207	0	0
Cu	528	48	9
Ni	1	0.1	10
Cd	38	0.2	0.5
Zn	759	3	0.5
Pb	229	0.3	0.1

(*) average values from three analyses

3.5 Concrete compressive strength

The concrete densities and compressive strengths of LWA-1, LWA-2, Lytag and LECA aggregates at 7, 14, and 28 days are given in Table 4. It is evident that concrete strength increased with age for all the aggregates examined. Concrete made with Lytag and IBA-derived aggregates achieved comparable compressive strengths at all ages. Lytag aggregate concrete attained a 7-day strength of 46 N/mm^2, which increased to 58 N/mm^2 after 28 days. Concrete made with LWA-1 achieved strengths of 48 N/mm^2 after 7 days, 55 N/mm^2 after 14 days, which increased to 59 N/mm^2 after 28 days. Concrete made with LWA-2 achieved a 28-day strength of 57 N/mm^2. The very low strengths of LECA are due to the low density, low strength and high porosity of the aggregates.

Table 4: Compressive strength results.

Aggregate	Density (g/cm^3)			Compressive strength (N/mm^2)		
	7	14	28	7	14	28
LWA-1	1.97	1.95	1.97	47.8	54.6	59.2
LWA-2	1.99	1.97	1.96	45.9	55.7	56.6
Lytag	1.88	1.87	1.85	46.2	53.2	57.8
LECA	1.73	1.70	1.68	21.5	23.3	23.9

4 Conclusions

The results presented and discussed in the present study show that it is possible to successfully manufacture lightweight aggregates from mixes of wastes, such as incinerator bottom ash and pulverized fuel ash.

The aggregate production process involves wet milling of the IBA/PFA mixes, pelletisation of the powder mixes and firing in a rotary kiln at high temperatures to produce sintered aggregates. Clay may also be added to aid pelletisation. IBA may also be mechanical ground to a suitable size that allows pelletisation. Lightweight aggregates with relatively high particle and bulk densities (in the range of 1.5-1.8 g/cm^3 and 0.8-0.9 g/cm^3 respectively) and water absorption values between 16-19% by dry weight have been produced. Although the IBA-derived aggregates show higher densities and water absorptions than Lytag, when used in concrete they developed comparable compressive strengths to Lytag concrete; the IBA-derived aggregates achieved 28-day strengths of about 57-59 N/mm^2 and Lytag achieved a 28-day strength of 58 N/mm^2.

The manufactured lightweight aggregates showed low buffering capacity. For most heavy metals investigated the IBA-derived aggregates LWA-1 (wet milled mix of IBA and PFA) showed similar leaching behaviour to Lytag for leachate pH values above 3. There was practically no detectable leaching of Cr, Ni, Cd and Pb from LWA-1 for leachate pH>3, although there was higher Cu and Zn leaching than Lytag for pH>3. Lytag had considerably increased Ni and Cd availability for leaching compared to LWA-1 under all pH environments. The potentially leachable fractions of heavy metals from LWA-1 are only Cu and Ni, which are leached at approximately 10% of the total metal concentrations present under aggressive leachate conditions (pH=3).

Further work is undertaken to determine additional concrete properties, such as tensile strength, modulus of elasticity, shrinkage and creep.

References

[1] Pfrang-Stotz, G., Reichelt, J. & Roos, R., Chemical-mineralogical valuation of the leachate potential of municipal solid waste incineration (MSWI) bottom ashes. *Waste Materials in Construction*, ed. G.R Woolley, J.J.J.M. Goumans, P.J. Wainwright, Elsevier Science B.V, Amsterdam, pp. 975-983, 2000.

[2] Chandler, A.J., Eighmy, T.T., Hartlén, J., Hjelmar, O., Kosson, D.S., Sawell, S.E., van der Sloot, H.A. & Vehlow, J., Municipal solid waste incinerator residues (Volume 67). *Studies in Environmental Science*, Elsevier Science B.V, Amsterdam, 1997.

[3] Clarke, L.B., *Applications for coal-use residues*, IEA Coal Research, UK, 1992.

[4] Wainwright, P.J. & Cresswell, D.J.F., Synthetic aggregates from combustion ashes using an innovative rotary kiln. *Waste Materials in Construction,* ed. G.R Woolley, J.J.J.M. Goumans, P.J. Wainwright (Eds.), Elsevier Science B.V, Amsterdam, pp. 759-767, 2000.

[5] Wainwright, P.J., Artificial aggregate from domestic refuse. *Concrete* pp. 25-29, 1981.

[6] Van der Sloot, H.A., Hoede, D., Cresswell, D.J.F. & Barton, J.R., Leaching behaviour of synthetic aggregates. *Waste Management,* **21,** pp. 221-228, 2001.

[7] Bhatty, J.I. & Reid, K.J., Lightweight aggregates from incinerated sludge ash. *Waste Management and Research,* **7**, pp. 363-376, 1989.

[8] Chiou, I.-J., Wang, K.-S., Chen, C.-H. & Lin, Y.-T., Lightweight aggregate made from sewage sludge and incinerated ash. *Waste Management*, article in press, 2006.

[9] Ingamells, C.O., Lithium metaborate flux in silicate analysis. *Analytica Chimica Acta*, **52(2)**, pp. 323-334, 1970.

[10] British Standards Institution (BSI), BS 812-2. Testing aggregates. *Methods for determination of density*, UK, 1995.

[11] British Standards Institution (BSI), BS EN 1097-3. Tests for mechanical and physical properties of aggregates. *Determination of loose bulk density and voids,* UK, 1998.

[12] Stegemann, J.A & Côtè, P., Method 11: Acid Neutralization Capacity, Test methods for solidified waste evaluation: a cooperative program. *Report No. EPA 3/HA/8,* Environment Canada, Ottawa, Ontario, 1991.

[13] British Standards Institution (BSI), BS 12390-3. Testing hardened concrete. *Compressive strength of test specimens,* UK, 2002.

[14] Brownell, W.E., Black coring in structural clay products. *Journal of the American Ceramic Society*, **40(6)**, pp. 179-187, 1957.

[15] Johnson, C.A., Acid neutralizing capacity of municipal waste incinerator bottom ash. *Environmental Science and Technology,* **29**, pp. 142-147, 1995.