KATHOLIEKE UNIVERSITEIT
LEUVEN

Proceedings of the **SECOND INTERNATIONAL**

SLAG VALORISATION SYMPOSIUM

THE TRANSITION TO SUSTAINABLE MATERIALS MANAGEMENT

18-20 April 2011
Leuven, Belgium

Editors: Peter Tom Jones, Yiannis Pontikes, Jan Elsen, Özlem Cizer, Luc Boehme, Tom Van Gerven, Daneel Geysen, Muxing Guo, Bart Blanpain

Organisers: MTM, centre for High Temperature Processes and Sustainable Materials Management, CR³, SMART-PRO²

Production of sintered lightweight aggregate using waste ash and other industrial residues

Christopher CHEESEMAN

Department of Civil and Environmental Engineering, Imperial College London,
South Kensington, London, SW7 2AZ, United Kingdom

c.cheeseman@imperial.ac.uk

Abstract

This paper reviews research on the use of a range of waste ashes, including pulverised fuel ash, for the production of lightweight aggregate. Manufacturing lightweight aggregate from pulverised fuel ash has been a highly successful ash reuse application. The drivers and barriers to the beneficial reuse of waste ashes are described, and these can be significant, particularly if the ash is classified as hazardous waste. Research on lightweight aggregate production using pulverised fuel ash, incinerator bottom ash, sewage sludge ash and mixed pulverised fuel ash and glass compositions is reviewed. The results demonstrate the importance of rapid firing in developing the micro-structural characteristics necessary for lightweight aggregate production, and the mechanisms occurring during production are outlined.

Introduction

The last 20 years have seen significant changes in the way waste materials are regarded and managed. In the early 1990's waste management research was primarily concerned with developing improved waste disposal methods, but as disposal costs particularly to landfill have increased, wastes have been increasingly regarded as potential resources for either direct reuse, processing into new materials or value extraction. As a result waste management is now widely regarded as resource management, with the aim to achieve resource efficiency by developing optimum reuse applications.

Industrial symbiosis is also having an increasingly important role.[1] This involves transfer of "waste" resources between organisations for mutual benefit, often with the waste resource becoming a new raw material. Developing industrial symbiotic links is becoming a significant driver for waste diversion, resource efficiency, innovation, new industries and economic development.

Drivers for resource efficiency include climate change, population growth and over exploitation of natural resources. These have led to various government initiatives that have resulted in increasing costs of energy, transport and waste disposal,

through for example landfill tax, limits on CO_2 emissions and taxes on resource extraction such as aggregate extraction taxes. Relevant EU and UK legislative changes are having a major impact on business development and innovation, and this is driving industrial symbiosis, and the development of more sustainable materials and emphasis on the low carbon economy. Legislative and business drivers are therefore absolutely fundamental to increased resource efficiency.

Figure 1 shows the life cycle of resources in the economy with the links between product disposal to product manufacture and materials production indicating materials flows in a resource efficient economy.[2] Making these important connections often needs innovative materials processing research.

Residues from thermal processes

Strategically important waste ashes and thermal treatment residues originate from a number of strategically important industrial sectors. Coal fired power stations produce pulverised fuel ash (PFA)/fly ash and furnace bottom ash (FBA). Energy from waste facilities combusting municipal solid waste (MSW) produce incinerator bottom ash (IBA) and air pollution control (APC) residues. Various types of biomass ash including sewage sludge ash (SSA), paper sludge ash (PSA), wood and other biomass/biofuel ashes are likely to become increasingly available. The steel industry

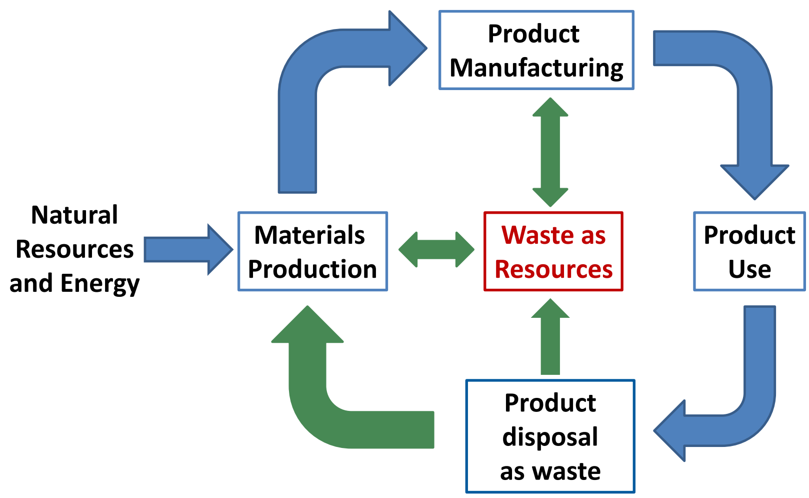


Figure 1: Diagram illustrating the flow of materials through a resource efficient economy, with innovation and research often needed to enable materials to flow from product disposal to product manufacture and materials production.[2]

produces thermal treatment residues such as ground granulated blast furnace slag (GGBS) and electric arc furnace (EAF) dust.

These types of thermal treatment residues typically contain a combination of glassy and crystalline phases and can have similar compositions to volcanic ashes. They are often alumino-silicate based, with some residual carbon content and other contaminants including heavy metals. As with volcanic ashes they can be pozzolanic, with potential for direct use as cement replacement materials. A key characteristic is variability in composition and physical properties, and therefore beneficiation processing or blending with other materials may be required before they can be used as raw materials. They may also be generated in relatively low volumes making commercial exploitation more difficult. Some types of ashes have fertiliser/nutrient value, allowing potential for disposal to land. However, concerns over leaching of heavy metals and other constituents into the environment often limit this potential outlet.

There are number of generic technologies that can be used to process residues from thermal treatment processes and waste ashes into new materials suitable for use in construction products. These include:

a) Sintered ceramic products involving further high temperature treatment;
b) Geopolymer and alkali activated cement systems;
c) Accelerated carbonation technologies;
d) Cement bound products;
e) Bitumen bound products.

A distinction needs to be made between those technologies that significantly transform the original chemical and physical properties of the thermal treatment residue and those that primarily involve encapsulation such as the cement and bitumen bound products. This is an important distinction, particularly when dealing with hazardous waste ashes.

The European Waste Catalogue (EWC) classifies waste materials and categorises them according to what they are and how they are produced. The use of hazardous wastes in products is challenging and must meet a number of criteria. The process used to manufacture the product must provide an acceptable level of treatment. The manufacturing process must have a permit to operate and treat hazardous waste issued by the relevant regulating authority. The proposed treatment must be regarded as equivalent to or ideally higher in the waste hierarchy than the existing disposal/recycling options available for the hazardous waste in question. Finally, the treatment cannot be based purely on dilution.

The production of geopolymers and accelerated carbonation technologies are the subjects of other contributions at this symposium, and therefore this paper will focus on sintered ceramic type products manufactured from thermal treatment residues. Of these, by far the most commercially important and successful is the production of lightweight aggregate. Lytag, the lightweight aggregate manufactured from pulverised fuel ash is probably the most successful manufactured ash derived product.

Lightweight aggregate (LWA)

Lightweight aggregate is increasingly sought after, particularly for use in the precast concrete industry, where it is used in a range of construction products. The resulting reduced weight of concrete components made using LWA aids off-site manufacturing and brings significant advantages during both construction and throughout the life of the building.

Ideal LWA pellets will have a fairly dense vitreous shell to reduce water uptake into the internal porous microstructure, a roughly spherical shape to aid flow during casting concrete, a low-density core containing a uniform distribution of fine pores, a relatively rough surface to aid bonding into the concrete, and high compressive strength. The density of normal weight aggregate is typically ~2.6 g/cm^3 whereas LWA for construction purposes should ideally have a density in the range ~1.2-1.4 g/cm^3.

LWA's are often natural materials such as pumice, volcanic slags and vermiculite. Manufactured LWA products are also currently produced from expanded clay, shale or slate, (Optiroc, Liapor, Perlite). Typical applications include lightweight concrete panels, blocks and other concrete products, lightweight fill, a medium for water filtration, and landscaping, drainage, agricultural and horticultural applications. Almost all LWA currently used in the UK is imported.

Sinter strand production of LWA from PFA[3-6]

Lytag is made from sintered pulverised fuel ash from coal fired power stations. The core of the manufacturing process is a sinter strand as shown in Figure 2. Green pellets produced by pan pelletisers fall onto a conveyor belt, which transports them to the sinter strand. The feeding box regulates the loading of green pellets on the sinter strand and maintains a fixed depth of approximately 18 cm. In order to maintain a constant bed depth the feeding box adjusts the speed of the sinter strand and therefore the velocity of the sinter strand depends on the amount of pellets being produced.

The sinter strand is typically about 2 metres wide and about 20 meters long. The first 3.5 metres is covered by an ignition hood, in which two recycled oil burners ignite the top of the bed. As the pellets move away from the ignition hood air is sucked through the pellets, and this causes the unburned carbon in the green PFA pellets to combust. The result is that a sintering zone moves down through the pellet bed, as shown schematically in Figure 2.

The wind boxes located beneath the sinter strand pull air through the bed. The total air flow rate is constant but can vary within the pellet bed and the outgoing air temperature is monitored. The aggregates at the end of the sinter strand are agglomerated together because they lightly bond to each other during sintering. A crash deck located immediately after the sinter strand crushes the sintered agglomerated LWA into individual discrete LWA pellets and also separates the LWA product from any remaining primary fine dust. The aggregates are then graded by particle size into fines, particles between 4 mm and 14 mm diameter, and particles greater than 14 mm. Each of these different particle size fractions can be used for different applications. Lytag is manufactured from PFA using this process. Fundamental to the technology is the rapid heating rate experienced by pellets on the sinter strand.

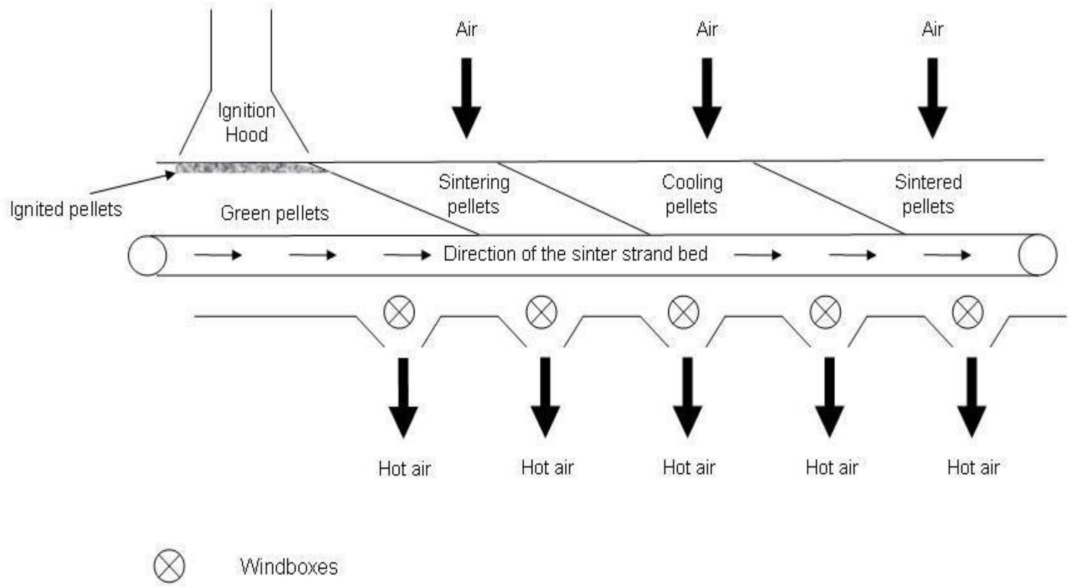
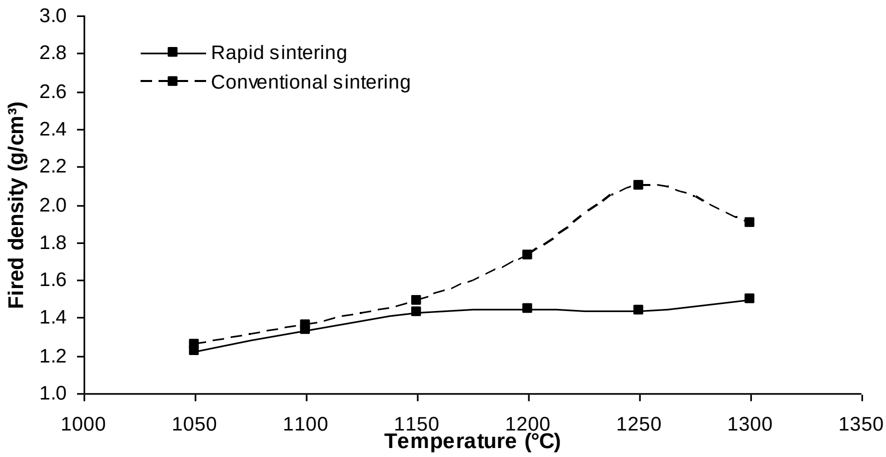


Figure 2: Schematic diagram of a sinter strand producing LWA. The top surface of the sinter bed is ignited as it passes under the ignition hood. Air is drawn through the green pellets and this produces a sintering zone that moves through the bed, with pellets experiencing a rapid temperature increase.[3]

Laboratory based research has compared the properties and microstructure of sintered PFA using conventional (20ºC.minute^{-1}) and rapid heating rates.[3,4] Results are given in Figures 3 for density and water uptake. Rapid heating was achieved by directly placing pressed PFA samples into a furnace preset at the sintering temperature. Slow sintered PFA samples show an increase in shrinkage and fired density and a reduction in water absorption as the sintering temperature increases, with maximum density obtained at around 1250°C. At higher temperatures samples show a bloating effect associated with the enlargement of closed porosity. This peak in density is not observed in rapidly sintered PFA. Rapid sintering at temperatures between 1150 and 1300°C resulted in constant values of shrinkage (6.5%), fired density (1.4 g/cm³) and water absorption (15%). During rapid sintering the residual carbon in the PFA is present in the sample at the sintering temperature, whereas conventional sintering removes the carbon at lower temperatures before sintering occurs.



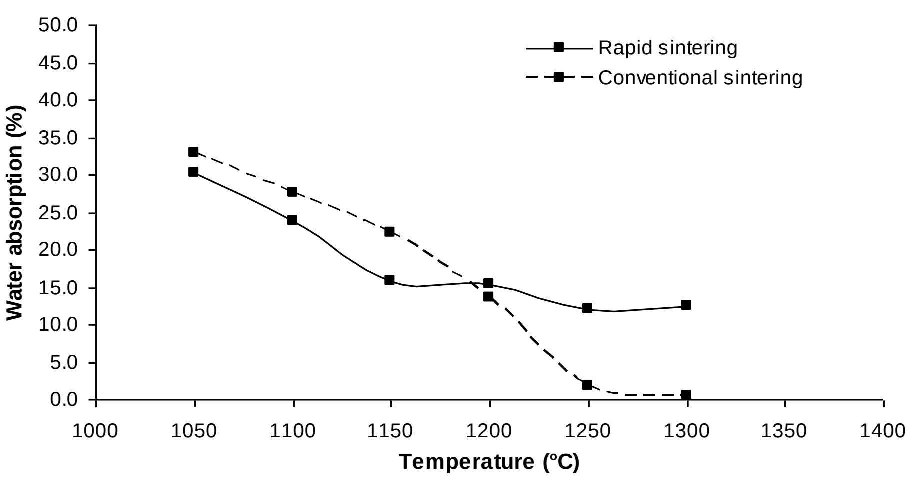


Figure 3: Effect of temperature on the fired density and water adsorption of rapid and slow sintered PFA pellets

The microstructures of rapid and slow sintered PFA are shown in Figure 4. Rapid sintering retains significant carbon in the core of the sintered sample. This carbon is believed to act as rigid inclusions that inhibit PFA sintering, limiting shrinkage and densification. Rapid sintering is also associated with black coring which is a characteristic in lightweight aggregate manufactured from PFA sintered on a sinter strand. The rapid heating rate experienced by PFA pellets and the associated inhibition of sintering by carbon is essential for producing sintered PFA products with properties appropriate for use as lightweight aggregate.

The micrographs in Figure 4 show samples sintered at 1150°C and illustrate the differences in microstructure resulting from the two sintering methods. The slow sintered samples show significant densification and a microstructure containing extensively closed porosity, while the rapid sintered pellets retain a porous microstructure, in agreement with the physical property data in Figure 3.

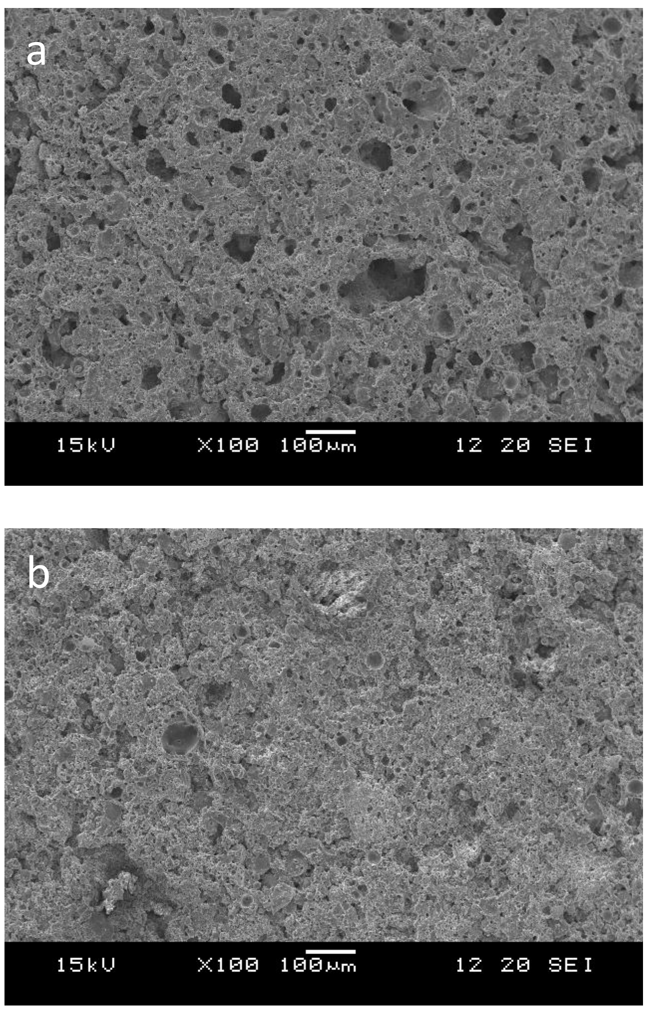


Figure 4: SEM micrographs of PFA samples sintered at 1150°C.
(a) rapid sintered; (b) slow sintered

Lightweight aggregate production from incinerator bottom ash (IBA)[7-11]

There are currently 24 energy-from-waste (EfW) plants operating in the UK, which range in capacity from 55.000 to 600.000 tonnes of municipal solid waste (MSW) per annum. Increasing restrictions on municipal solid waste (MSW) disposal to landfill will result in greater waste recycling, with energy recovery from the residual waste in EfW plants also expected to increase. A key research aim is to optimise resource management of the resulting ashes, the air pollution control (APC) residues and incinerator bottom ash (IBA). IBA is currently used in fairly low grade bulk civil engineering applications or it is landfilled.[5]

The fraction of municipal solid waste IBA with a particle size less than 8 mm represents about 40 weight percent of the total and is particularly problematic as effective reuse applications are not always available. IBA with this size fraction was obtained from a major UK EfW facility and has been milled, formed into pellets and rapidly sintered in a rotary furnace at temperatures between 900 and 1080°C. The effect of sintering temperature on density and water absorption of the sintered pellets is shown in Figure 5.

Sintering at temperatures between 1000 and 1050°C produced pellets with physical properties comparable to Lytag, the commercially available LWA manufactured from sintered PFA. Major crystalline phases present in milled bottom ash were quartz (SiO_2) and calcite ($CaCO_3$), while sintered pellets contained diopside ($CaMgSi_2O_6$), wollastonite ($CaSiO_3$) and clinoenstatite ($Mg_2Si_2O_6$). Leaching of heavy metals from sintered bottom ash pellets in water and under acid conditions (leachate pH 2-7) was investigated. Rapid sintering at relatively low temperatures significantly reduced aqueous leaching compared to milled ash, with Pb and Zn only leaching under aggressive conditions (leachate pH 3). The trials indicated that relatively simple processing of the finer fraction of IBA allows this problematic waste to be manufactured into lightweight aggregate with potential uses in a range of construction products and geotechnical applications.

Lightweight aggregate production from sewage sludge ash (SSA)[12,13]

Incineration is a necessary alternative to both land spreading and disposal to landfill for sewage sludge, and is currently used to dispose of approximately 19% of UK sludge. The dried solids content of sludge has relatively high calorific value (20-40 MJ/kg) and if the moisture content is reduced by pressing or centrifuging then autothermic combustion occurs. There are currently two fluidised bed sewage sludge incinerator plants operating in East London, with a third currently under construction. The Beckton and Crossness sludge incinerators have a combined capacity to process 373.000 tonnes of dewatered sewage sludge per year, and

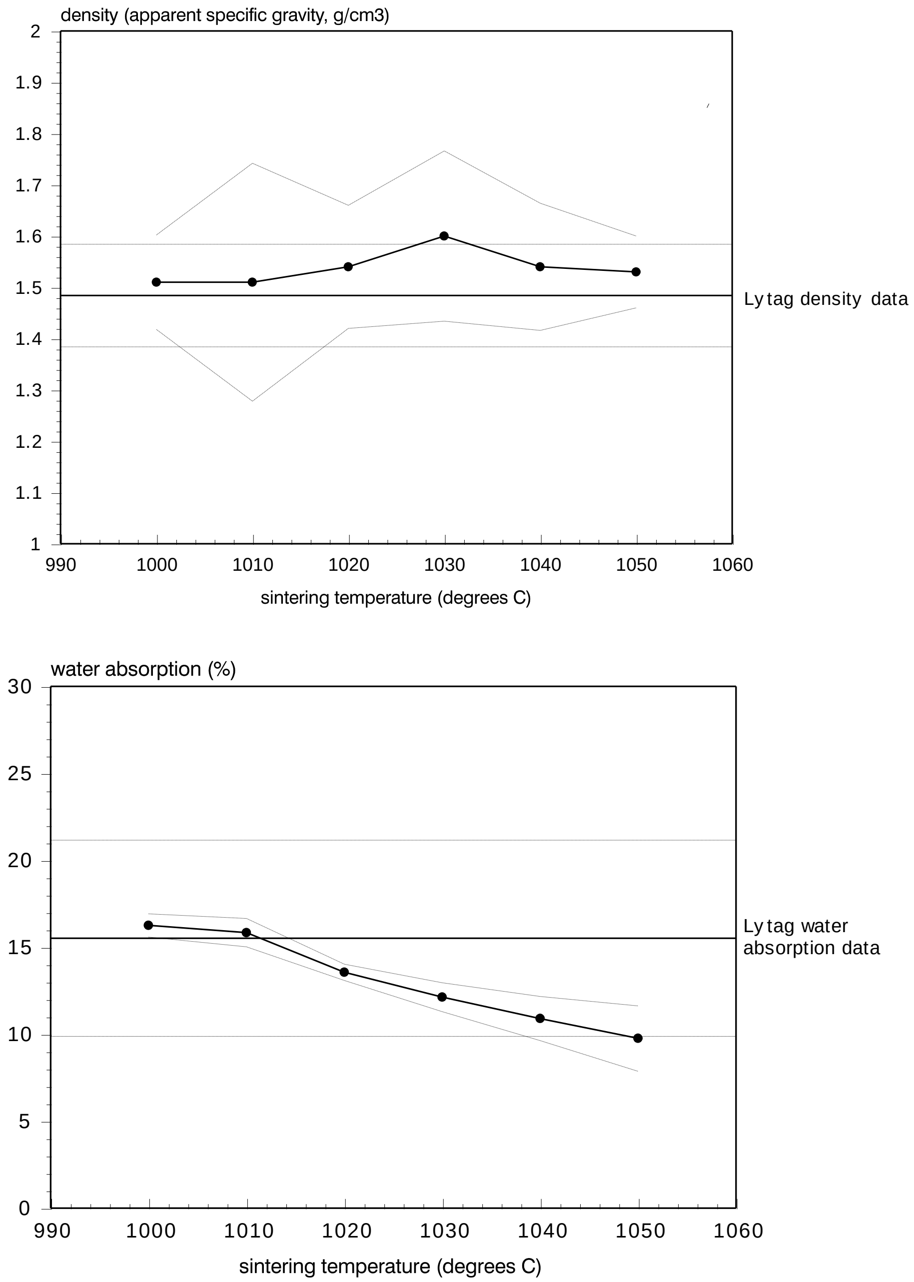


Figure 5: Effect of firing temperature on the properties of sintered IBA pellets, a) density (apparent specific gravity), b) 24-hour water absorption.

approximately 1% of the original mass of sludge forms the sterile and inert sewage sludge ash (SSA). This is currently transported off-site for disposal in landfill. Tightening legislation and increasing landfill disposal costs are providing incentives to develop alternative economically viable reuse and recycling options.

The properties of lightweight aggregate manufactured from sewage sludge ash have been investigated. The ash was mixed with a clay binder, formed into approximately spherical pellets and rapidly sintered in a rotary tube furnace at temperatures

between 1020 and 1080°C. Selected physical properties of sintered ash pellets relevant to use as lightweight aggregate have been determined, including density (apparent specific gravity) as shown in Figure 6, water absorption and compressive (crushing) strength. These have been compared to the properties of commercially available lightweight aggregate (Lytag). Sewage sludge ash pellets sintered over a range of temperatures were found to have lower densities than Lytag, low water absorption when fired between approximately 1050 and 1080ºC, and individual pellet strengths comparable to Lytag.

Major crystalline phases present in both as-received and sintered sewage sludge ash were quartz (SiO_2), the calcium magnesium phosphate mineral whitlockite ($Ca_7Mg_2P_6O_{24}$) and hematite (Fe_2O_3). Figure 7 shows the typical microstructure of sintered SSA pellets and these have the ideal vesicular characteristics required for a LWA.

Manufacturing LWA from sewage sludge ash may become increasingly viable as landfill disposal costs continue to increase and the costs of alternative natural aggregates obtained from increasingly distant locations increase. Sewage sludge incinerators are situated in urban areas, close to construction activity and the ash has relatively consistent composition compared to many waste derived ashes.

The results indicate the potential for manufacturing high quality lightweight aggregate from the sterile, inert ash produced by sewage sludge incineration, using relatively simple processing and low temperature sintering.

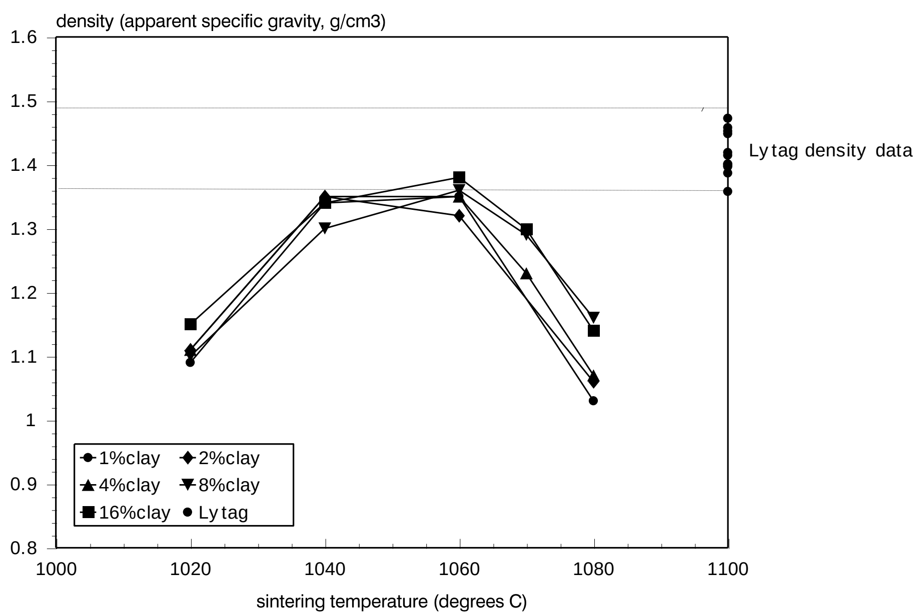


Figure 6: Effect of sintering temperature on the density of LWA produced from SSA

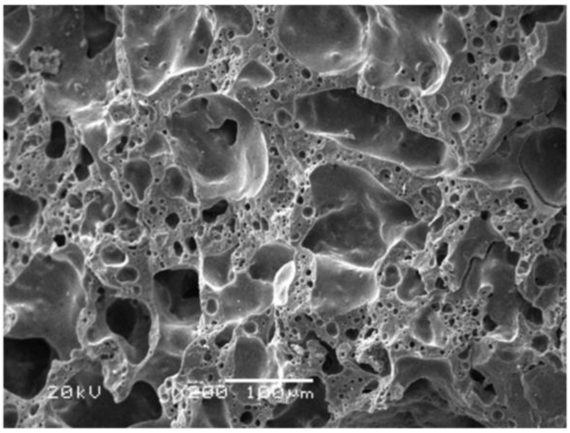


Figure 7: Fracture surface of SSA LWA pellets sintered at 1070°C showing an ideal vesicular microstructure required for LWA

Lightweight aggregate production from coal fly ash and glass[14]

The effect of glass addition on the processing, physical properties and microstructure of pelletised lignite coal fly ash from the Megalopolis power station in Greece have also been investigated. Fly ash/glass mixes were rapidly sintered at temperatures between 1040ºC and 1120ºC in a rotary furnace, and the density, water absorption and pellet strength have been determined. Sintering 60:40 fly ash: waste glass mixes at 1120ºC produced lightweight aggregate pellets with a mean density of 1.5 g/cm^3, water absorption of ~16% and crushing strength of 7.3 MPa, which are all comparable properties to Lytag.

Major crystalline phases in sintered materials were quartz (SiO_2), albite ($NaAlSi_3O_8$), moissanite (SiC), hematite (Fe_2O_3), wollastonite ($CaSiO_3$) and diopside ($CaMg(Si_2O_6)$). The work indicated that fly ash from the Megalopolis power station combined with waste glass could be used to manufacture lightweight aggregate with properties comparable to commercially available products.

Discussion

The production of lightweight aggregate is a technically and commercially viable reuse application for certain types of waste ash. The sintering process effectively vitrifies heavy metals into the microstructure so that they are not leachable, and the original crystalline phases present in the ash may not be present in the sintered product. The process therefore has potential to be regarded as an effective treatment for some selected hazardous waste ashes. The associated "gate fee" for using these types of ash will also increase the commercial viability of the process.

Rapid heating to the sintering temperature is essential to form the micro-structural characteristics required for lightweight aggregate. When pelletised ash samples are placed directly into the furnace at the sintering temperature the viscosity of the glass phase rapidly falls and this should initiate viscous phase sintering. However, significant unburned carbon is often present in the bulk of the sample. Near the surface the carbon is oxidised to CO_2 or CO and can be released from the sample. Within the bulk of the sample there is insufficient O_2 for oxidation of the carbon to occur, and the residual unburned carbon particles act as rigid inclusions, producing transient stresses that oppose sintering. Rigid carbon inclusions inhibit normal sample densification and are likely to contribute to the forming the microstructure required for LWA production.

The black coring observed in rapidly sintered PFA samples and other ash derived LWAs may be due to the residual unburned carbon content present in the central part of the samples. Only the thin layer close to the surface is associated with complete carbon combustion. However black coring is also reported to be due to the formation of reduced iron species. The microstructure of manufactured lightweight aggregates often contains isolated spherical voids and these are formed by the simultaneous evolution of gases following the volatilisation of trace components in the ash at temperatures where the glassy phase is in the correct viscosity range to trap the gases.

LWA typically sells in the UK for between £ 40 to £ 180 per tonne depending on grade, quantity, application and location. Therefore there is significant scope to cover the processing costs associated with LWA manufacture from waste ash that typically involves particle size reduction by milling, pelletising and relatively low temperature rapid sintering. These costs will vary depending on a number of factors including exact processing methods used.

Conclusions

Resource efficiency and industrial symbiosis are important drivers for innovation and economic development. There is increasing demand for lightweight aggregate for use in precast products for off-site manufacturing. The manufacture of lightweight aggregate from pulverised fuel ash produced by coal fired power stations is a proven ash valorisation technology. Research has demonstrated the potential for manufacturing lightweight aggregate from a number of different problematic waste ashes. Development of appropriate vesicular microstructures to give the required properties of lightweight aggregate requires rapid firing and sintering processes. Lightweight aggregate production may offer further opportunities for slag valorisation.

Acknowledgements

The author would like to acknowledge all the co-authors in the papers listed in the references for their contribution to lightweight aggregate research completed at Imperial College London.

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