

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:



Novel approaches to the valorisation of ashes using aggregation by carbonation

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Abstract

Accelerated carbonation technology (ACT) is a treatment for calcium and magnesium rich wastes using a reaction with carbon dioxide gas. The process can facilitate the reuse of previously unusable hazardous wastes as new construction materials, such as engineering fills and aggregates. During 2010, two large-scale trials were conducted using ACT. The first project explored the capture of carbon from flue gasses using municipal solid waste incinerator (MSWI) air pollution control (APC) residues. It was found that carbon could be effectively stripped from a flue gas as it is passed through a bed of APC material. In the second trial, which built on the previous approach, an industrial-scale plant was constructed to produce aggregates for use in concrete blocks. As a result, over two hundred tonnes of aggregate from APC residues were produced.

Introduction

Carbonation is a naturally occurring reaction, which can be accelerated by exposing reactive materials to elevated concentrations of carbon dioxide gas. Many wastes are reactive with carbon dioxide, particularly those derived from industrial thermal processes, including incineration residues.¹⁻⁶

The carbonation reaction occurs in stages.⁷ In summary, carbon dioxide gas hydrates in water to form carbonic acid (H_2CO_3), which then reacts with calcium ions (dissolved from the reactive material) to form calcium carbonate (CaCO_3). As carbonate minerals are formed, the pH of a material is reduced achieving minimum solubility of many regulated metal contaminants.^{8,9} Metal availability can also be reduced by the formation of insoluble metal carbonates.^{10,11} Calcium carbonate is more voluminous than the reactant minerals, resulting in reduced porosity and aids the retention of contaminants.¹²⁻¹⁴ Complete carbonation of a material can reduce the release of metals by up to 80%.¹⁵

During the carbonation process, calcium carbonate precipitates to form an interlocking lattice, creating a cementitious bond between constituent grains. By exploiting this mechanism, fine grained APC residues are cemented together by the reaction with carbon dioxide to form granules or pellets, with reuse potential.¹⁶

Nearly 5.2 million tonnes of waste was incinerated during 2007 in the UK, an increase of six percent on 2006.¹⁷ The amount of incinerated waste is set to increase further with the construction of as many as 20 new incinerators. The current 33 incinerators have a combined permitted capacity of 8.6 million tonnes. If approved, the new facilities will provide a further 12 million tonnes of burning capacity.¹⁷

Incinerator flue gasses are acidic, and may also contain low levels of dioxins and volatile metals. Lime and carbon are the usual materials added to flue stack to neutralise the acid and remove pollutants. The resulting dust, or Air Pollution Control residue (APCr), is collected in bag filters before the cleaned flue gas is released to the atmosphere.¹⁸ Around 128000 tonnes of APC residues are currently generated in the UK each year, which is expected to increase by a further 40000 tonnes in the near future.^{19,20}

The present work discusses the results of two large-scale field trials of Accelerated Carbonation Technology (ACT). These trials aimed to first demonstrate the point-source collection of waste carbon dioxide and then convert hazardous municipal solid waste incinerator (MSWI) APCr into both a material suitable for use as engineering fill, and an aggregate for use in concrete construction block manufacture. The first trial explored the potential of combusted landfill gas as a source of carbon dioxide for use in the controlled accelerated carbonation of imported MSWI APCr and other waste. The carbonated product will then be used in ground engineering works on site. In the second field trial, a full-scale production plant was constructed to manufacture aggregate from MSWI APCr. The plant utilised a staged approach to treat the incoming waste, blend with selected reagents, and manufacture the aggregated product.

Landfill gas derived carbon dioxide

Closed non-hazardous waste landfills are potential sources of carbon dioxide. Municipal waste landfills are responsible for around 5% of the total greenhouse gas emissions²¹ in the UK. Landfill gas is generated from the decomposition of biodegradable waste, and is composed primarily of methane, carbon dioxide, nitrogen and oxygen. Gas collection wells are installed in closed landfills, and the gas is often burnt in flare stacks or gas engines.

A landfill site located in the south-east of England was selected for the trial. The site covered approximately 23 hectares, and domestic and commercial wastes were tipped for two decades prior to the site closure in the early 1990's. The landfill comprised a series of radial cells, which were capped. A final cap was placed when the site closed completely, and a gas collection system and flare stack were installed. Settlement due to decomposition of the waste has led to significant subsidence of the ground surface, and the cap has been compromised in several places. Accelerated carbonated-treated wastes will be utilised in a demonstration-scale restoration of one part of the site.

Plant setup

The existing gas collection system was modified to provide gas to a facility placed alongside the existing flare compound (see Figure 1). A modified industrial boiler was installed, and the combustion of landfill gas was optimised. The key variables for efficient combustion are the gas chemistry, residence time, the temperature of the burn, and the turbulence of the gas flow.²² A programmable logic controller (PLC) was used to monitor these variables and maintain optimal burning conditions for the production of carbon dioxide gas. By burning the gas in the PLC-controlled burner it was possible to create a flue gas containing up to 14% carbon dioxide.

Gas from the burner was extracted by connecting a pipe to the flue, and drawn off using a compressor pump. The gas was passed through a condenser, cooled and then piped to the treatment plant, comprising bulk storage for waste, a means of blending wastes together (or with reagents), and the carbonation reactor (see Figure 2). The MSWI APCr was delivered to the site in 5 tonne loads by powder tanker, and stored in a silo. A second silo was used for storing reagents. Both silos were connected to a

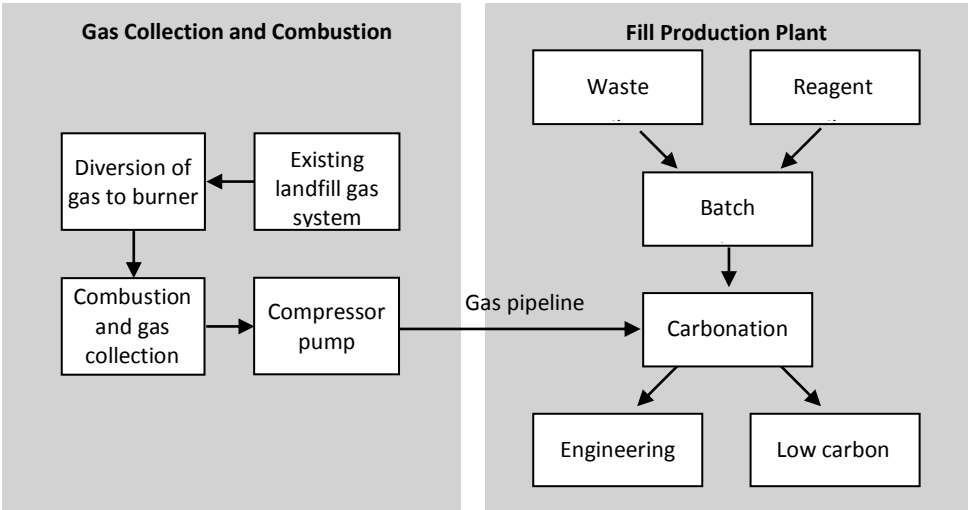


Figure 1: Flowchart of the gas collection and fill production process



Figure 2: Fill production plant

computerised batch mixer. The ingredients were prepared and fed into a rotating carbonation reactor receiving a controlled supply of combustion gas, containing carbon dioxide. The carbon dioxide portion of the combustion gas reacted with the waste, and gas leaving the mixer was depleted of carbon dioxide.

Methods

The composition of the gas entering and exiting the carbonation reactor was analysed using a landfill gas analyser (Gasdata GFM410) connected to an in-line sampling port on the gas pipeline. Monitoring lasted three hours, with measurements taken approximately every 10 minutes. Carbon dioxide captured as carbonate in the treated product was measured by thermogravimetry (Stanton-Redcroft STA-780). The total concentrations of regulated contaminants in the untreated MSWI APCr were measured by X-Ray Fluorescence (Bruker AXS S8 Tiger). Contaminant release from the untreated MSWI APC and the treated product was tested using a single-stage dynamic water leaching test (BS EN 12457-2), as specified in the Landfill Regulations, and analysed by ICP-OES.²³ The leaching and analysis measurements were carried out by a third party UKAS accredited laboratory.

Results

Low purity carbon dioxide flue gas was passed through a reactor containing MSWI APCr that was reactive with carbon dioxide. The results of monitoring the composition of the gas entering and exiting the reactor are shown in Figure 3.

The gas entering the reactor consistently contained between 13 and 14% carbon dioxide. During the first ten minutes of the process, the CO₂ in the gas stream was reduced to below 2%. After ten minutes, carbon dioxide in the exhaust gas began to increase. Around 100 minutes into the process, the difference in CO₂ concentration across the reactor was within 1%, indicating that the reaction had largely completed. Carbon dioxide uptake in the APCr increased rapidly in the first 40 minutes. The rate of uptake then began to decrease, following the pattern of decreased CO₂ consumption. This behaviour is a result of increasing consumption of the reactive phases within the ash. As carbonation proceeds, reactive products also build up on the surface of particles, inhibiting further reaction with the gas.²⁴ Agitating material whilst carbonating promotes the rate of reaction,²⁵ and was achieved through the rotation of the carbonation reactor. The tumbling action promoted the formation of pellets ranging from sand to cobbles (see Figure 4).

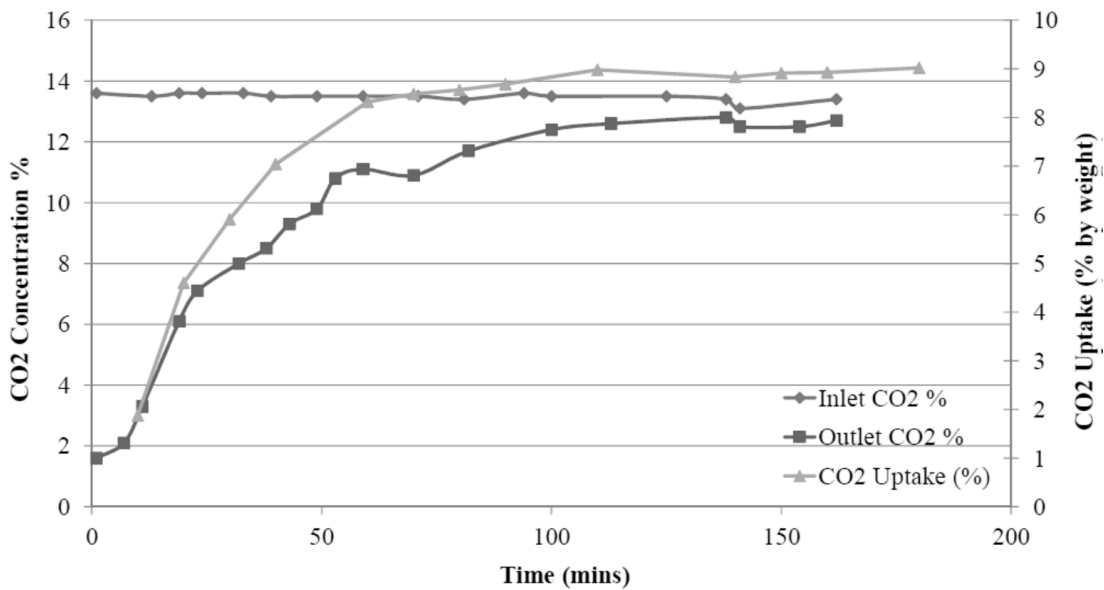


Figure 3: Comparison of gas inlet and outlet concentrations, and carbon uptake in the APCr



Figure 4: Photograph of a) untreated APC, b) granules of carbonated product

Waste destined for landfill is assessed against Waste Acceptance Criteria (WAC), as specified in the Landfill Regulations. These impose limits upon the leaching concentrations of certain metals. Three classes of waste exist: inert, stable non-reactive, and hazardous. The total concentrations of these metals present in the solid MSWI APCr are shown in Table 1. These indicate the maximum potential release of these metals through leaching.

Table 1: Total Metal Content of MSWI APCr

Determinant	Unit	MSWI APCr
Antimony	mg/kg	346
Arsenic	mg/kg	485
Barium	mg/kg	196
Cadmium	mg/kg	22
Chromium	mg/kg	48
Copper	mg/kg	315
Lead	mg/kg	6774
Mercury	mg/kg	2.7
Molybdenum	mg/kg	2.4
Nickel	mg/kg	7.4
Selenium	mg/kg	0.9
Zinc	mg/kg	6110

Accordingly, the untreated ash is considered as a hazardous waste on account of the levels of lead in the leachate, which exceeded the hazardous WAC limit (see Table 2). However, zinc was not a significant problem in the leachate, suggesting that it may already be chemically bound in the APCr. After treatment by carbonation, the lead levels in the leachate were reduced to below inert landfill limits, and the leachate concentrations of barium, chromium, molybdenum, and zinc, were also reduced.

Table 2: Leached metals from untreated and treated MSWI APCr

Determinant	Unit	Untreated MSWI APCr	Treated MSWI APCr	Inert WAC	Stable Non-Reactive WAC	Hazardous WAC
Antimony	mg/kg	0.07	0.03	0.06	0.7	5
Arsenic	mg/kg	0.1	0.07	0.5	2	25
Barium	mg/kg	42.3	19.7	20	100	300
Cadmium	mg/kg	< 0.01	< 0.01	0.04	1	5
Chromium	mg/kg	3.3	1.8	0.5	10	70
Copper	mg/kg	0.77	< 0.04	2	50	100
Lead	mg/kg	68.4	< 0.09	0.5	10	50
Mercury	mg/kg	< 0.01	< 0.01	0.01	0.2	2
Molybdenum	mg/kg	0.72	0.16	0.5	10	30
Nickel	mg/kg	< 0.03	< 0.03	0.4	10	40
Selenium	mg/kg	0.06	< 0.02	0.1	0.5	7
Zinc	mg/kg	3	< 0.20	4	50	200

WAC ~ Waste Acceptance Criteria for landfill, Hazardous levels in **bold type**

Site restoration

It is intended that the materials made during the full-scale trial of this technology will be used to restore a small section of the landfill, which has suffered from erosion of the soil capping or because gas migration has killed the vegetation. An area measuring ten metres by ten metres will be stripped of its cap, and then re-engineered using the carbonated APCr. The restoration area will be divided into a series of cells to trial the carbonated ash for different engineering functions. These will include as a gravel substitute for drainage, as a regulating layer to protect the liner, and blended with imported materials to create soils for the final capping layer.

Aggregate production

In the second field trial, a commercial-scale plant for turning MSWI APCr residues into aggregate was constructed. Over the short trial period, in excess of 200 tonnes of aggregate was manufactured, which was validated for use as an aggregate in concrete blocks.

Plant setup

The production plant had multiple stages (see Figures 5 and 6). Silos were placed on site for receiving deliveries of MSWI APCr by a 25 tonne powder tanker. Following treatment to reduce the levels of leachable contaminants, reagents were employed

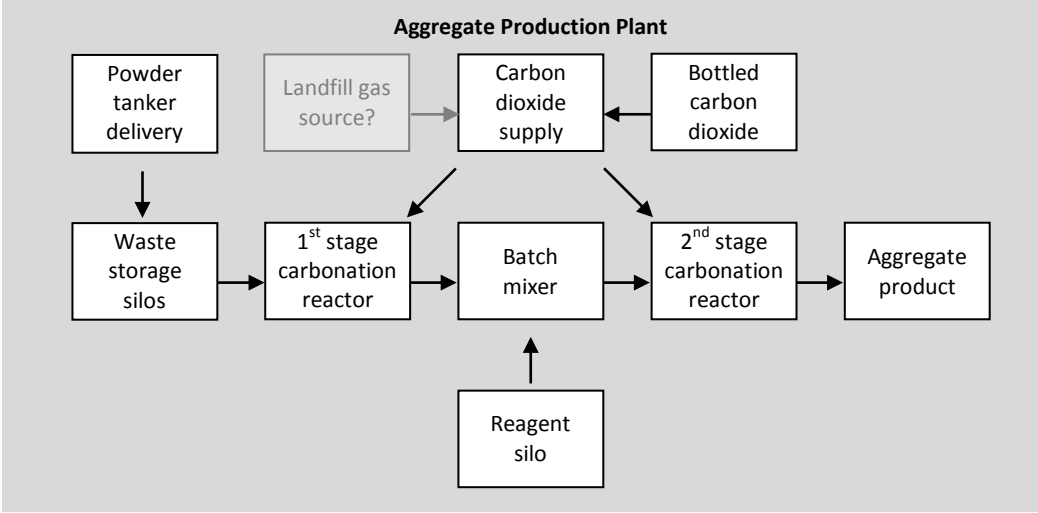


Figure 5: Flowchart of the aggregate production process

where necessary, to produce a mixture which was then pelletised in the presence of pure carbon dioxide. This was supplied from pressurised bottle banks, rather than a point source of carbon dioxide gas, such as that exploited at the landfill site. The pelletised hardened product was stored in an adjacent bay, and screened to produce the required grading for use in the on-site block making process.

Methods

The pelletised aggregates were tested to European Standard testing according to BS EN 1744 (chemical tests),²⁶ BS EN 13055 (mechanical tests),²⁷ BS EN 1097 (physical tests).²⁸ These tests were conducted by a third party accredited laboratory. Carbon dioxide captured as carbonate in the treated product was measured by thermogravimetry, total concentrations of regulated contaminants in the untreated MSWI APC by X-Ray Fluorescence, and contaminant release using a single stage dynamic water leaching test (BS EN 12457-2)²³ and analysed by ICP-OES. The leaching

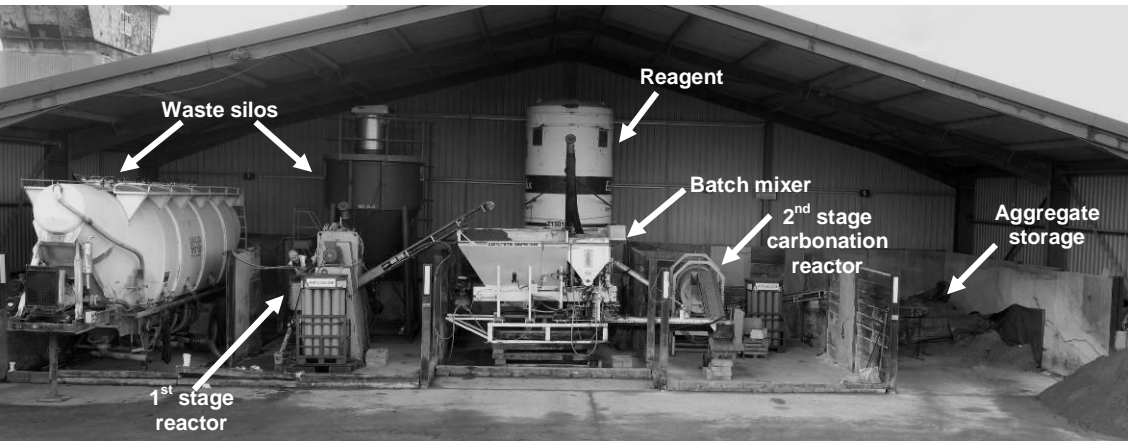


Figure 6: Aggregate production process

and analysis measurements were carried out by a third party UKAS accredited laboratory.

Results

The total metal content of the second source of MSWI APCr is shown in Table 3. Leaching data is shown in Table 4. The levels of lead leaching from the untreated ash exceeded the WAC hazardous threshold. An appreciable level of zinc, although within the stable non-reactive limit, was also measured. After processing the MSWI APCr into aggregate, the leachate levels of zinc, lead and selenium were reduced to with inert WAC limits. The lead levels in particular were reduced by almost two orders of magnitude. Copper and mercury levels were reduced to below detection limit.

Table 3: Total Metal Content of MSWI APCr

Determinant	Unit	MSWI APCr
Antimony	mg/kg	24.3
Arsenic	mg/kg	< 0.5
Barium	mg/kg	476
Cadmium	mg/kg	123.1
Chromium	mg/kg	109.3
Copper	mg/kg	480
Lead	mg/kg	1449
Mercury	mg/kg	3.3
Molybdenum	mg/kg	7.9
Nickel	mg/kg	36
Selenium	mg/kg	3
Zinc	mg/kg	560

After production, the aggregate is stored, and then screened to the required particle size grading (see Figure 7). The aggregate was tested and compared to British Standard limits, which are shown in Table 5. British Standard limits often only require that the specification of the material is reported, and not that it must meet a set value. The aggregates produced are designated as lightweight aggregate (see also contribution by Chris Cheeseman elsewhere in this Symposium Book), since their bulk density does not exceed 1200 kilograms per cubic metre (kg/m^3).²⁷ Apparent particle density was measured as 2.4, which exceeds the limit value for lightweight aggregate of 2 mega grams per cubic metre (Mg/m^3). However, either particle density or bulk density can be used to classify the aggregate.²⁷

Table 4: Leached metals from untreated MSWI APCr, processed aggregate, and concrete blocks containing the APCr aggregate

Determinant	Unit	Untreated MSWI APCr	MSWI APCr Aggregate	MSWI APCr Aggregate Block	Standard Block	Inert WAC	Stable Non-Reactive WAC	Hazardous WAC
Antimony	mg/kg	< 0.03	< 0.03	0.08	0.02	0.06	0.7	5
Arsenic	mg/kg	< 0.01	< 0.01	0.02	0.03	0.5	2	25
Barium	mg/kg	5.8	12.3	0.9	0.3	20	100	300
Cadmium	mg/kg	< 0.01	< 0.01	< 0.01	< 0.01	0.04	1	5
Chromium	mg/kg	3.4	9.2	0.2	0.2	0.5	10	70
Copper	mg/kg	0.4	< 0.1	< 0.1	< 0.1	2	50	100
Lead	mg/kg	143.9	1.8	0.01	0.01	0.5	10	50
Mercury	mg/kg	0.02	< 0.001	0.1	0.1	0.01	0.2	2
Molybdenum	mg/kg	2.1	0.8	0.6	0.5	0.5	10	30
Nickel	mg/kg	< 0.06	< 0.06	< 0.06	< 0.06	0.4	10	40
Selenium	mg/kg	0.12	0.08	0.1	0.04	0.1	0.5	7
Zinc	mg/kg	37,8	0,6	0,07	0,03	4	50	200

WAC ~ Waste Acceptance Criteria for landfill, Hazardous levels in **bold type**

Sulfate and chloride levels in lightweight aggregate are not directly regulated. Instead, the levels are set for the final end product, measured as either a percentage of the total weight of the block or as a proportion of the weight of the cement. The

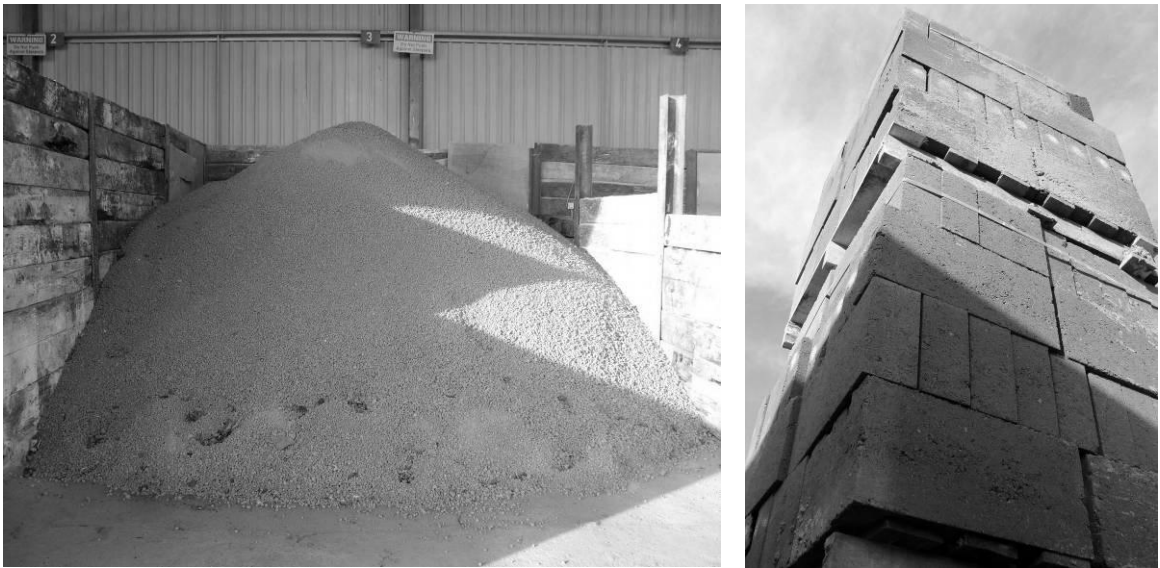


Figure 7: Manufactured, screened carbonated aggregate (left), concrete blocks produced from aggregate (right)

blocks were manufactured using a mixture containing 10% by weight of carbonated aggregate. Balancing the proportions of the raw ingredients in the block mixture is important to achieve the desired product. Accordingly, the sulfate and chloride levels were well within the limits applicable to the finished product.

Table 5: Properties of carbonated aggregate

	Loose Bulk Density, kg/m ³	Water Soluble Chloride, %	Total Sulfate, %	Acid Soluble Sulfate, %	Apparent Particle Density, Mg/m ³	Water Absorp- tion, %	Block Strength, MPa	Block Bulk Density, kg/m ³
APCr Aggregate	950 ^a	1.1 ^b	2.0 ^b	1.2 ^b	2.4 ^c	19.6 ^c	4.2 ^d	1661
Limit Value	1200 ^{e,f}	0.2 ^g	1 ^h	1 ⁱ	2.0 ^{e,f}	Not specified ^e	➤ 3 , 6 d	1100- 1900 ^d

^a Measured according to BS EN 1097-3²⁸, ^b Measured according to BS EN 1744-1²⁶, ^c Measured according to BS EN 1097-6²⁸, ^d Specified for Hanson construction blocks²⁹, ^e According to BS EN 13055-1²⁷, ^f Loose bulk density or apparent density may be used²⁷, ^g According to BS EN 206 based upon the total weight of cement in the final concrete product³⁰, ^h According to BS EN 13139 based upon the total weight of the final product³¹, ⁱ According to BS 8500³².

The graded aggregate was directly added into the concrete block making process as a replacement for natural gravel. Examples of the blocks produced are shown in Figure 7. The compressive strength of the blocks was measured at 4.2 MPa, which exceeds the published specification for the standard block at 3.6 MPa. Bulk density of the blocks was 1661 kg/m3, which falls within the range of standard block types available. Samples of the blocks were despatched to a third party accredited laboratory for testing the release of regulated contaminants. The results are shown in Table 4, compared to a standard concrete block not containing MSWI APCr derived aggregate. Antimony, mercury and molybdenum levels were within stable non-reactive WAC limits, and close the upper limit for inert. The remaining elements were within inert WAC limits, or below detection limit. These results were comparable to the commercial blocks tested. Elevation of the concentrations of arsenic, antimony and mercury in the block compared to the treated APCr suggests that they are derived from the existing raw materials used to make the concrete blocks on site.

Conclusions

A pilot scale trial was set up to demonstrate the capture and use of waste carbon dioxide gas for the accelerated carbonation of hazardous municipal waste incinerator air pollution control residue (MSWI APCr). The work was completed at a former landfill site, where landfill gas rich in methane was diverted from a flare stack and

burnt in a specially designed computer controlled boiler that maximised the amount of carbon dioxide produced. After contact with the ash, the combustion gas was substantially stripped of its carbon dioxide content, demonstrating it was possible to harness a point source of this gas for beneficial use. Leaching from the carbonated product was within stable non-reactive landfill limits, and was therefore suitable for use on-site as a geotechnical medium. The carbonated product will be used for the restoration of a small area of the landfill and for further monitoring and performance testing.

A second trial was established to construct and operate a full-scale production plant to create aggregate from MSWI APCr. The process incorporated multiple stages to prepare the raw ash, blend with reagents, and manufacture a pelletised product. After treatment and processing, the leaching from the aggregate was reduced to within stable non-reactive limits. The aggregate was classified as lightweight, and was used to manufacture concrete construction blocks. Leaching was comparable to a standard commercially available block. The bulk density and strength of the blocks conformed to the required specifications.

Acknowledgements

On the landfill capture project, the financial and administrative support of the UK Environment Agency is gratefully acknowledged, as is the support of Professor Stefaan Simons of University College, London. The authors would also like to thank Mark Orsbourn and Steven Greig of Carbon8 Aggregates Ltd for their substantial contribution to the successful execution of the work reported here.

References

1. S. Diener, L. Andreas, I. Herrmann, H. Ecke, and A. Lagerkvist, "Accelerated carbonation of steel slags in a landfill cover construction", *Waste Management*, **30** (1) 132-139 (2010).
2. D. N. Huntzinger, J. S. Gierke, L. L. Sutter, S. K. Kawatra, and T. C. Eisele "Mineral carbonation for carbon sequestration in cement kiln dust from waste piles", *Journal of Hazardous Materials*, **168** (1) 31-37 (2009).
3. R. Baciocchi, G. Costa, E. Lategano, C. Marini, A. Poletti, R. Pomi, P. Postorino, and S. Rocca, "Accelerated carbonation of different size fractions of bottom ash from RDF incineration", *Waste Management*, **30** (7) 1310-1317 (2010).
4. Q. Chen, D.C. Johnson, L. Zhu, M. Yuan, and C.D. Hills, "Accelerated carbonation and leaching behavior of the slag from iron and steel making industry", *Journal of University of Science and Technology Beijing, Mineral, Metallurgy, Material*, **14**, (4) 297-301 (2007).
5. S. Arickx, T. Van Gerven, and C. Vandecasteele, "Accelerated carbonation for treatment of MSWI bottom ash", *Journal of Hazardous Materials*, **B137** 235-243 (2006).
6. D.C. Johnson, "Accelerated carbonation of waste calcium silicate materials", *Sci. Lecture Series*, Society of Chemical Industry, (2000).

7. A.Maries, "Measurement of gas consumption during accelerated carbonation of Portland cement mortar", in: *Proceedings of the 2nd International Conference on Accelerated Carbonation for Environmental and Materials Engineering*, Rome, 1-3 October 2008.
8. X. Li, C.D. Hills, P.J. Carey, and S. Simons, "Making aggregates from waste and carbon dioxide", in: *Proceedings international 23rd cement and concrete science conference*, University of Leeds (2003).
9. L. Van Ginneken, V. Dutré, W. Adriansens, and H. Weyten, "Effect of liquid and supercritical carbon dioxide treatments on the leaching performance of a cement-stabilised waste form" *Journal of Supercritical Fluids*, **30** 175-188 (2004).
10. T. Van Gerven, D. Van Baelen, V. Dutre, and C. Vandecasteele, "Influence of carbonation and carbonation methods on leaching of metals from mortars", *Cement and Concrete Research*, **34** 149-156 (2004).
11. S.B. Shaffique, J.C.Walton, N. Gutierrez, R.W. Smith, and A.J. Tarquin, "Influence of carbonation on leaching of cementitious wasteforms", *Journal of Environmental Engineering*, **124** 463-467 (1998).
12. E. Rendek, G. Ducom, and P. Germain, "Carbon dioxide sequestration in municipal solid waste incinerator (mswi) bottom ash" *Journal of Hazardous Materials*, **128** 73-79 (2006)
13. B. Johannesson, and P. Utgenannt, "Microstructural changes caused by carbonation of cement mortar" *Cement and Concrete Research*, **31** 925-931 (2001).
14. L.C. Lange, C.D. Hills, and Poole, A.B. "The effect of accelerated carbonation on the properties of cement-solidified waste forms", *Waste Management*, **16** 757-763 (1996).
15. M. Fernández-Bertos, S. J. R. Simons, C.D. Hills, and P.J.Carey, "A review of accelerated carbonation technology in the treatment of cement-based materials and sequestration of CO₂", *Journal of Hazardous Materials*, **112** 193-205 (2004).
16. P.J.Gunning, C.D. Hills, and P.J. Carey, "Production of lightweight aggregate from industrial waste and carbon dioxide", *Waste Management*, **29** 2722-2728 (2009).
17. Environment Agency. <http://www.environment-agency.gov.uk>, Accessed 16.01.2010 not a very useful reference any more detail?
18. C. Macleod, R. Duarte-Davidson, B. Fisher, B. Ng, D. Willey, J. P. Shi, I. Martin, G. Drew, S. Pollard, "Modeling human exposures to air pollution control (APC) residues released from landfills in England and Wales", *Environment International*, **32** (4) 500-509 (2006).
19. C. Lampris, J.A. Stegemann, C.R. Cheeseman, "Solidification/stabilisation of air pollution control residues using Portland cement: Physical properties and chloride leaching", *Waste Management*, **29** (3) 1067-1075 (2009).
20. D. Amutha Rani, A.R. Boccaccini, D. Deegan, and C.R. Cheeseman, "Air pollution control residues from waste incineration: Current UK situation and assessment of alternative technologies", *Waste Management*, **28** (11) 2279-2292 (2008).
21. E. Chalvatzaki, E. and M. Lazaridis, "Estimation of greenhouse gas emissions from landfills: Application to the Akrotiri Landfill Site (Chania, Greece)", *Global NEST Journal*, **12** (1) 108-116 (2010).
22. Environment Agency, "Guidance on landfill gas flaring", Available at <http://www.environment-agency.gov.uk>, Accessed 09.09.2010.
23. British Standard Institute, BS EN 12457, "Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges", (2002).
24. J. Jerga, "Physico-mechanical properties of carbonated concrete", *Construction and Building Materials*, **18** 645-652 (2004).
25. M. Fernández-Bertos, X. Li, S.J.R. Simons, C.D. Hills, and P.J. Carey, "Investigation of accelerated carbonation for the stabilization of MSW incinerator ashes and sequestration of CO₂", *Green Chemistry*, **6** 428-436 (2004).
26. British Standard Institute, BS EN 1744, "Tests for the chemical properties of aggregates", (1998).

27. British Standard Institute, BS EN 13055, "Lightweight aggregates – Part 1: Lightweight aggregates for concrete, mortar and grout", (2002).
28. British Standard Institute, BS EN 1097, "Tests for mechanical and physical properties of aggregates", (1996).
29. Heidelberg Cement. <http://www.heidelbergcement.com>. Accessed 07.06.2010.
30. British Standard Institute. BS EN 206-1, "Concrete", (2000).
31. British Standard Institute. BS EN 13139, "Aggregates for mortar", (2002).
32. British Standard Institute. BS 8500-1, "Concrete – complimentary British Standard to BS EN 206-1", (2006).