Institution: University of Greenwich		
Unit of Assessment: 12 - Engineering		
Title of case study: Mineralisation of CO_2 for waste valorisation: Innovating the waste management and the construction sectors through commercialisation of carbon-negative building aggregate		
Period when the underpinning research was undertaken: January 2000 to December 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Colin D Hills	Professor in Environment and Materials Engineering	01/02/1999 – present
Nimisha Tripathi	Research Fellow	04/07/2016 – present
Paula J Carey	Principle Lecturer	01/08/1998 – 21/03/2013
Period when the claimed impact occurred: August 2013 to July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Prof CD Hills' novel CO_2 mineralisation technology (known as ACT) led to a spin-out company Carbon8 Systems. ACT enables industrial solid waste to be diverted from landfill and CO_2 gas from the atmosphere into construction materials. Three UK licensed fixed aggregate-manufacturing plants deploy ACT to produce 350 kt/pa of carbon-negative aggregates, sequestering 0.13 Mt of CO_2, replacing 1.8 Mt of virgin/quarried stone and saving £60 M in landfill taxes ACT is recently deployed in world's first mobile 'plug-and-play' device known as the 'CO_2ntainer', which directly removes CO_2 from flue gas. This small-footprint innovation helps industry to manage their wastes. Vicat, France have deployed the world's first commercial 'CO_2ntainer', saving €2.5 M/pa.

2. Underpinning research

The research led by **Hills** underpinning this case study extends cement-based stabilisation/solidification of waste and contaminated soil with an added accelerated carbonation step (Lange, Hills and Poole, 1996). Studies **[R1]** on the field performance of carbonate-cemented soils showed increased resilience to weathering. Further, key observations led to an engineered artificial 'stone' made from fine particulate waste via a managed carbonation reaction-step (using ACT).

InnovateUK and other support **[**e.g., UCL 2004-5; **R2]** informed process engineering design and the physical properties of mineralised products, which as carbonated aggregates met British Standards (BSEN 13055) and that CO_2 can be permanently mineralised in carbonated products. Furthermore, carbonated waste-based products had potential to meet 'end of waste' (EoW) (EU Waste Framework Directive). 'EoW' was granted in 2011. Waste is diverted from landfill (currently 350 kt/pa), and environmental impacts are reduced, natural resources are preserved, and alternative low-carbon light-weight materials for construction are available **[R3]** (EPSRC G03303113).

The nature and arisings of carbonate-able EU waste-streams **[**Interreg IV project led by UoG; 2013-15; **Hills**- PI, **G1],** highlighted significant matrials engineering potential. One hundred waste 'types' incl. thermal residues were processed into carbonated light-weight products. Biomass ash residues from France (via partner University, Picardie Jules Verne) formed one of the different aggregates incorporated into construction blocks. These demonstrated advantages over conventional blocks via: (a) greater resilience to hygric and thermal variations, (b) lightweight, and (c) embodied carbon, i.e., carbon-negativity.

A joint doctoral program (UOG-Dal) at Dalhousie, Canada investigated the mechanical properties of mineralised fine and coarse aggregates and concluded that properties were commensurate with natural analogues (limestone), further supporting the fitness-for-purpose of carbonated aggregated products **[**e.g., **R4]**.

Building on the Interreg 4A project **[G1]**, a collaboration with the CSIR, Gov. of India (2015-on) (HEIF funded), investigated high-volume biomass waste/ashes (**Hills**- PI; **Tripathi**- RF, 2016-on) providing new insight into the carbonation potential of these wastes. A route (2018-20) to produce a bespoke carbonate-able binder for use in light weight composite materials, and a unique mineralised product that could partially substitute for Portland cement **[R5]** was discovered. Our research findings support accelerated carbonation of solid wastes as a Carbon Capture, Storage and Utilisation (CCUS) technology.

Two new patent applications (2017 (granted **[P1]**), and 2019), complementing existing protection (2008, 2010) further support the commercial development of the carbonation technology. This IP exploits advantages arising from a synergistic relationship between different carbonate-able wastes, and the process technology underpinning a mobile carbonation plant (the CO_2ntainer). The CO_2ntainer can directly strip CO_2 from flue gas into the mineralisation process - another 'first' in this field; now being used commercially in France for Vicat. The engineering design of the mobile plant comprising two interconnected shipping containers was particularly challenging.

Our research has resulted in >100 publications. The UN Environment Programme (UNEP) used our work in its GEO6 Report (Pan-European Assessment) (see page 60 for introduction, p 219 for further details/case study) as an exemplar of low-carbon technology. The Global CO2 Initiative (GCI) 2016 (see p 15, 19 (figure 3.1), 30) report states our technology as world leading (2016). The aggregate product was UK recycled product of the year 2013.

3. References to the research

R1. Antemir, A., **Hills, C.D., Carey P.J.**, Gardner, K.H. and Crumbie, A.K. (2010). Long-term Performance of Aged Waste Forms Treated by Stabilisation/Solidification. Journal of Hazardous Materials, 181 (1-3) : pp 65-73 https://doi.org/10.1016/j.jhazmat.2010.04.082
R2. Fernández Bertos, M., Li, X., Simons, S.J.R., **Hills, C.D.** and **Carey, P.J.** (2004). Investigation of accelerated carbonation for the stabilisation of MSW incinerator ashes and the sequestration of CO2. Green Chemistry, 6, pp. 428-436 https://doi.org/10.1039/B401872A
R3. Gunning, P., **Hills, C.D. and Carey, P.J.** (2010). Accelerated Carbonation Treatment of Industrial Waste, Journal of Waste Management, 30, pp. 1081-90 https://doi.org/10.1016/j.wasman.2010.01.005
R4. Lake, C., Choi, H., **Hills, C.D.,** Gunning, P. and Manaqibwala, I. (2016). Manufactured aggregate from cement kiln dust. Environmental Geotechnics. pp. 1-12. ISSN 2051-803X (Online) https://doi.org/10.1680/jenge.15.00074
R5. Tripathi, N., Hills, C.D., Singh, Raj S. and Singh, Jamuna S. (2020). Offsetting anthropogenic carbon emissions from biomass waste and mineralized carbon dioxide. Scientific Reports 10, 958 https://doi.org/10.1038/s41598-020-57801-5

P1. Hills, C.D. and Carey, P.J. (2017). Improved Production of Aggregates. WO2017/194953 A1 (Patent granted, Singapore).

G1. Colin D Hills, PI. Interreg IVA (Channel) project: Sustainable Aggregate Production with Imbibed Carbon Dioxide (SAPICO2). Value: €860,000, 2013-2015.

4. Details of the impact

The ACT process **[**e.g., **R2]** developed by **Hills** and team underpinned the spin-out company Carbon8 Systems (C8S) in 2006 **[I1a]**, and its operating arm, Carbon8 Aggregates (C8A) in 2010 **[I1b]**. In 2012, following the first 'End of Waste' agreement of its kind for C8A's aggregate by the Environment Agency (the aggregate obtained the status as a product, or secondary raw material), C8A established the first fixed ACT manufacturing facility in Brandon, Suffolk, using pure, bottled CO_2 gas. In doing so, a 'CO_2-utilisating/sequestering', management solution for municipal solid waste incinerator (MSWI) air pollution control residues (APCr) was offered to the UK for the first

time. The carbonated aggregates entered the UK aggregate market, competing with virgin stone and offtake is subject to commercial supply agreements.

The research innovated UK Waste management, as the APCr-based aggregate enabled the first ever 'carbon-negative' building block.
The C8A's APCr-based aggregate was used to make carbon-negative blocks by a block manufacturing company, Lignacite Ltd. The high-performance masonry product developed promted the aggregate to be declared as the UK's 'Best Recycled Product'. Key to this recognition was that the 'low-carbon' aggregates **[**e.g., **R1**, **R2]** captured and sequestered more CO_2 than was emitted during their manufacture, and reduced environmental harm.

Since REF 2014, the UoG's CO_2 mineralisation research has enabled the spin-out company to increase supplies of high-quality carbon-negative, cost-effective and sustainable light-weight aggregates (compliant with, e.g., BSEN 13055; 13242 and ISO 9001), to the construction industry. This has enabled >100 kt/pa of APCr (currently 25% of UK's APCr production) **[I2]** to be diverted from landfill via its incorporation in carbonated APCr-based aggregates.

Process scaling-up by C8A (subsequently re-named OCO Technology Ltd.) increased the UK supply of the low-carbon APCr-based aggregate.
Since REF 2014, C8As UK fixed plants have increased from 1 to 3, and currently c.a. 350 kt/pa aggregates enter the UK market for use in construction blocks (e.g., CEMEX, Lignacite, Hairds, Forterra and Thomas Armstrong).

The continued research and its commercial implementation (2014-2020) have contributed to social, economic and environmental impacts, and environment policy as evidenced below:

(a) social impacts are realised in terms of (i) reduced environmental harms (diversion of c.a. 550 kt of APCr from landfill, so using waste as a resource and reducing the leaching into the environment), and (ii) employment opportunities (C8A/OCO and C8S have >110 staff) **[**e.g., **I5]**,
(b) environmental impacts include (i) reduced risks from waste (as above), (ii) CO_2 sequestration/utilisation (unpublished data shows the direct mineralisation of CO_2 to be c.a. 130 kt), and (iii) low-carbon aggregate products (1.3 Mt of manufactured aggregates contained ca. 0.13 Mt of mineralised CO_2 and replaced ca. 1.8 Mt of virgin/quarried stone (1 t of carbonated aggregate replaces 1.4 t of natural aggregates, as the aggregate is a light-weight product), (iv) reduced carbon footprint of carbonated aggregates/blocks (carbonated aggregate is carbon negative) provides additional benefits to the businesses to achieve circular economy and lower emissions **[I2]**, and
(c) economic impacts include: (i) value to waste, as landfill avoidance saves £94/t in tax currently (typically 120€/t in the EU) excluding gate fees, and aggregates sales are at £10/t (€20/t in EU), (ii) employment generation (as indicated above), (iii) savings on landfill costs, with unpublished data showing ca. 550kt APCr to date was transformed into 1.3 Mt of aggregates, saving £60 M in landfill tax fees, whilst preserving >1.8 Mt of virgin stone, and generating £13 M worth of aggregate sales. Therefore, the economic and environmental advantages of the carbonated aggregates are substantial, as the process involves very little energy, since it is reliant on the CO_2 reactivity of the waste material **[R1**, **R2**, **I2]**.

ACT is recognised as an exemplar of CCUS technology by, e.g., CO2Value Europe (>70 members including Solvay, Mitsubishi and Total), GCI, and CO2Chem KTN (a network of >1000 members). The importance of CO_2 utilisation to Europe's future economy is illustrated by recent policy recommendations (CO2Value Europe, 2020-2024) **[I3a**, **I3b]**, with mineralisation considered for inclusion in the European Emissions Trading Scheme (ETS) **[I3c]**.

From 2016, **Hills** and team's research **[**e.g., **R1**, **R2]** underpinned the construction of two new ACT plants by C8A to enhance capacity in manufacture of the APCr-based aggregate (Avonmouth, 2016; Leeds, 2017) **[I1b]**. The APCr management capability of the company has increased 3-fold. As such the aggregate has a carbon footprint of -44 kg/t, meaning that it is truly carbon negative. As a result of supply not yet meeting construction block industry demand, 10-

30% w/w (total aggregate weight) aggregate is typically used as a substitute for virgin stone. The substitutions will still lower the carbon footprints of the blocks, which they comprise.

C8A rebranded as OCO Technology Ltd. in 2019 **[I1b]** and has grown significantly with a current annual turnover of £13 million (2019), >90 staff, and a supply 350Kt/pa of carbonated manufactured aggregate, being equivalent to 0.5Mt of virgin stone/pa. Production is projected to rise to 700 kt/pa over the next 3 years **[I2]** as OCO continues to increase its client base, including Thomas Armstrong and Tilbury MSWI **[I1b**, **I5]**. Further, an exclusive development agreement with Mitsubishi Corporation (to cut their GHG emissions to net zero by 2050) has been signed **[I1b]**.

New innovation has enabled a mobile carbonation plant to directly extract CO_2 from flue gas and treat other (non-APCr) wastes.

A new development is a containerised mobile plant ('CO_2ntainer') that extends the technological solution, away from large remote fixed plants that use bottled gas. The innovative 'CO_2ntainer', is 'plug-and-play' ready and directly uses flue gas as the source of CO_2 for the carbonation process. With InnovateUK support, C8S trialled the 'CO_2ntainer' in Canada with CRH (>€27.6 Bn; 80,000 employees) in Ontario (2018-19) and Hanson (part of CRH) in the UK (2019-20) **[I1]**.

The success of these trials and Innovate UK funding **[I3c]** led to the first commercial deployment of ACT by Vicat, the French national cement company, in 2020 **[I4**, **I5]**.Vicat's testimonial **[T1]** states: "*It is Vicat's intention to deploy the CO_2ntainer at our other cement plants in France as part of our commitment to become CO_2 neutral by 2050*. *We are convinced that ACT is a key technology to reach this target"*. Vicat (>€2.74 Bn; >9000 employees) have installed the 'CO_2ntainer' for treating cement by-pass dusts at their cement plant in Lyon. The 24 kt/pa of carbonated aggregates produced are being used internally. The commercial benefits for Vicat are savings of ca. €2.5 M/pa at the cement plant from avoidance of landfill and reduction in virgin stone requirement. The global licence signed with Vicat is worth £8 M. Recent investment in C8S has totalled £2 M.

Following, AVR started an advanced demonstration of the 'CO_2ntainer' at its MSWI in Duvien (September 2020). AVR are the Netherlands largest Energy from Waste company and are using ACT to "ultimately target zero waste" by combining their APCr and pre-captured CO_2 (400 kt/pa) into products. This significant advance enables technology integration at complex industrial facilities and the valorisation of solid and gaseous wastes at source, e.g., Arcellor Mittal steel plants. Arcellor's testimonial **[T2]** states:…."*the latest commercial innovation concerning a mobile plant that can be employed at the sites of smaller emitters….combining solid and gaseous emissions is a game changer"*.

Technology leadership has been widely acknowledged **[**CO2Value Europe, GCI, UNEP and CO2Chem KTN; e.g., **I6**, **I7**, **I8a]**. In November 2016, BBC Radio 4 (audience typically 10M/week) exclusively featured ACT in its 30-minute 'Costing the Earth' programme and emphasised its potential contribution towards addressing CO_2 emissions **[I9]**. The overseas export potential was recognised by the Queen's Award for 'Enterprise: Innovation' in September 2017 **[I8b]**. The award citation stated "world leader in permanent capture of carbon dioxide using industrial wastes to form new products".

The research was subsequently featured on BBC SE News in 2017 (ca. 0.5M viewers), discussing the realised benefits of ACT for waste management, including a laboratory-demonstration of the technology and the C8A Avonmouth plant **[I10]**. Invited articles and presentations evidence the emerging importance of ACT/mineralisation at UK and European levels. The technology was recognised in the UNEP Pan-European Assessment GEO6 report (2016) as "a demonstrable contribution to the developing European circular economy" **[I7]** UNEP/UNECE 2016. The report highlights environmental state/ science-policy trends underpinning decision-making in the Pan-European region **[I7]**. A key emphasis is the 2030 Agenda for Sustainable Development and its Goals. Recognition of ACT as an exemplar came from the 3 sponsor organisations: the UNEP, European Environment Agency and Economic Commission for Europe **[I7]**. More recently (2020), **Hills** was invited to contribute a Faraday Discussion (for wider dissemination of mineralisation

technology). These recognitions have associated impact, e.g., informing the client-base, public and stakeholders of the academic/research, commercial and environmental benefits of Greenwich's low-carbon technology.

The innovation(s) have informed teaching and research at the University of Greenwich.
The development of curricula in Engineering since 2014 has included specific themes related to low-carbon technology, and sustainable construction materials. Bespoke lectures on ACT at UG and PG-level courses (e.g., Environmental Engineering), research opportunities and training at Master's and PhD (incl. ERASMUS) are offered. **Hills** delivers sessions at the CO2Chem Summer/Winter Schools (2017–2020) bringing the benefits and limitations of ACT to >80 PhD students/pa from across the country, as part of their training. Furthermore, C8S represents the 'Utilisation' cohort within the Carbon Capture and Storage and Association (CCSA) -the trade association (>60 members incl. Shell, BP and OCO) promoting the commercial deployment of CCUS *and* the Zero Emissions Platform.

5. Sources to corroborate the impact

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I1b. www.oco.co.uk
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I3a. https://www.co2value.eu/wp-content/uploads/2020/06/CVE-paper-on-CCU-in-ETS-Recommendations-for-the-revision-of-the-Monitoring-and-Reporting-Regulation-MRR.pdf
I3b. CO2ValueEurope https://www.co2value.eu/wp-content/uploads/2019/11/CO2-Value-Europe-Manifesto-2019-November.pdf
I3c. Curia.europa.eu (2020). *Case Number C-460/15.* Available online at: Curia Europa Case No C-460/15
I4. InnovateUK 2020, www.innovateukedge.ukri.org/news/Carbon-capture-tech-converts-cement-dust-construction-aggregate
I5. Cemnet 2020, Vicat signs decarbonisation agreement with Carbon8 Systems (cemnet.com), 16 July, 2020.
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I10. BBC NEWS FEATURE
T1: Testimonial, Mar 2021: Laury Barn es-DavinVicat, Scientific Director, Research and Development, Vicat, France
T2: Testimonial, Jan 2021: Manfred Van Vlierberghe, CEO, ArcelorMittal, Belgium.