

Impact case study (REF3)

Institution: Sheffield Hallam University		
Unit of Assessment: UOA12 - Engineering		
Title of case study: Technologies, innovation, materials and training for maintenance, repair and restoration of concrete infrastructure		
Period when the underpinning research was undertaken: 2000 - 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:
Pal Mangat	Professor and Director of the Centre for Infrastructure Management (CIM)	1993 – present
Fin O'Flaherty	Professor	1997 – present
Paul Lambert	Visiting Professor at CIM	2005 – present
Period when the claimed impact occurred: 2014 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Research into concrete materials and structures, by Sheffield Hallam's Centre for Infrastructure Management (CIM), has generated professional practice and economic impacts throughout the REF period through: (i) certified competence training to 251 bridge inspectors with GBP1,300,000 investment by UK and international bridge authorities; (ii) commercialisation via AMX Solutions Ltd of research on bridge management expert systems adopted by 45 local authorities, 6 national and 8 international bodies, generating income [text removed for publication]; (iii) commercialisation of low carbon alkali activated cementitious materials (AACMs) through C-Probe Ltd. and Liquid Granite Ltd., and with Mott MacDonald Ltd., generating [text removed for publication] combined income since 2014, underpinning investment [text removed for publication].

2. Underpinning research

Mangat and O'Flaherty's work concerns durability of reinforced concrete structures. It focusses on long-term performance of concrete repair in highway structures through investigations concerned with interactions between repair patches and substrate concrete in combination with innovative materials research specifically addressing the limitations of concrete repair materials. This work is embodied in three underpinning streams of research:

1. Bridge management modelling and expert system design

Research was undertaken into the development of new computer models for evaluating the effects of long-term deterioration processes in concrete, such as shrinkage cracking [R1], chloride diffusion, and reinforcement corrosion on performance of repair [R2]. These computer models, together with the comprehensive databases created of defects and repair performance, enabled predictions of durability, severity, and extent of defects. The research was applied (through a Knowledge Transfer Partnership project [i]) to develop an expert system for optimal repair in highway bridges. This was developed to facilitate implementation of the "Management of Highway Structures code of Practice" produced in 2005 and the "Inspection Manual for Highway Structures" produced by the UK Bridges Board in 2007. The resultant software is protected by copyright held by *AMX Solutions Ltd.*

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2. Repair of structures

The research on concrete repair materials and their long-term performance in bridge repairs [R1, R2], was extended to cathodic protection (CP) for corrosion remediation in concrete-steel composite structures with the award of a Royal Society Industrial Fellowship to Dr Paul Lambert to work with Mangat at SHU from 2001 to 2005 [ii]. Lambert is the Head of Materials and Corrosion Technology at *Mott MacDonald* and a Visiting Professor at SHU since 2005. The research on CP initially concentrated on numerical modelling of CP systems and their experimental verification. This facilitated the investigation of optimum CP system designs for corroding reinforced concrete and steel framed masonry structures [R3] and led to the development of a dual function, corrosion protection and structural strengthening, CP system for reinforced concrete structures [R4]. This was underpinned by the research on alkali activated cementitious materials (AACMs) (section 2.3), which produced an electrically conductive AACM matrix for the dual function CP anode which has been patented by a start-up company (*C-Probe*) and applied in 22 commercial contracts by *C-Probe* and *Mott McDonald* (section 4.2.1).

3. AACM (Geopolymer) Compositions

Research by the team identified the principle of using inorganic alkali material to activate waste-derived reactive powders, thereby avoiding use of high CO₂-producing hydraulic cement. Experimental investigations determined chemically optimised compositions of multiple reactive powders, filler and activator [R5], so characterising the key parameters governing properties such as strength and durability. Further work developed admixtures capable of giving control over AACM setting time and shrinkage, thereby addressing practical considerations such as placement, compaction, on-site curing and long-term durability. Formulations suitable for different repair methods were then developed through an EU Regional Development Scheme grant [iii]. Industrially sponsored research from 2010 [iv] determined methodologies by which to exploit the excellent adhesive properties and electric conductivity of AACMs to achieve dual function anode systems which offer both CP and structural strengthening to concrete structures. AACMs proved to be fire resistant at temperatures exceeding 1100°C, significantly out-performing cement-based or polymer-modified materials. Compositions have been developed which include fire resistant AACM concrete, AACM mortars for repair and spray applications, and electrically conductive AACM mortars for CP applications. Research funded by the EPSRC [v] has supported underpinning research on material characteristics such as microstructure of the AACMs [R6] which has been related to properties such as strength, shrinkage, fire resistance and durability [R7]. It has also utilised agri-waste materials in AACMs together with industrial waste materials. Calculations for our AACM binder, based on the CO₂ emission factors of its constituents, gives 76% lower CO₂ equivalent emission factor than ordinary Portland cement (OPC). These underpinning research outputs provide critical support for commercialisation of the AACMs.

3. References to the research

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- R1. MANGAT, P. S. and O'FLAHERTY, Fin (2004). Analysis of interfacial shrinkage stresses in patch repairs. *Magazine of concrete research*, 56 (7), 375-385. <https://doi.org/10.1680/macr.2004.56.7.375>
- R2. O'FLAHERTY, F and MANGAT, P (2003). Recommendations for the European pre-standard for concrete repair. In: NAUS, D.J.,(ed.) *2nd International RILEM Workshop on Life Prediction and Aging Management of Concrete Structures*, RILEM Publications SARL, 237-245 https://www.rilem.net/gene/main.php?base=500218&id_publication=34&id_papier=875

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- R3.** LAMBERT, P, MANGAT, P, O'FLAHERTY, F and WU, Y (2008). Cathodic protection of steel framed masonry structures - experimental and numerical studies. *Materials and structures*, 41 (2), 301-310. <https://doi.org/10.1617/s11527-007-9240-2>
- R4.** LAMBERT, P, VAN NGUYEN, C, MANGAT, P, O'FLAHERTY, F and JONES, G (2015). Dual function carbon fibre fabric strengthening and impressed current cathodic protection (ICCP) anode for reinforced concrete structures. *Materials and structures*, 48 (7), 2157-2167. <https://doi.org/10.1617/s11527-014-0300-0>
- R5.** Mangat, P.S., Khatib, J.M., and Wright, L., "Optimum utilisation of FGD waste in blended binders" *Proceedings of the Institution of Civil Engineers, Construction Materials* 159, 119, (2006) <https://doi.org/10.1680/coma.2006.159.3.119>
- R6.** MANGAT, P.S., OJEDOKUN, Olalekan (2018). Influence of curing on pore properties and strength of alkali activated mortars. *Construction and Building Materials*, 188, 337-348. <https://doi.org/10.1016/j.conbuildmat.2018.07.180>
- R7.** Mangat, P. S., Ojedokun, O.O. (2020). Free and bound chloride relationships affecting reinforcement cover in alkali activated concrete. *Cement and Concrete Composites*, 103692. <http://doi.org/10.1016/j.cemconcomp.2020.103692>

All outputs were rigorously peer-reviewed prior to publication. Outputs **R3** and **R4** resulted from a Royal Society Industrial Fellowship and **R6** and **R7** resulted from EPSRC–Newton Bhabha Funding.

Key grant information

Royal Society Industrial Fellowship “Novel Electrochemical Solutions for corroding Steel Framed Masonry Heritage Structures”, 2001-05, GBP93,000

EU Regional Development Funding (SY/4/23/NBP/1432) 2003-04, GBP114,562

EPSRC, Newton-Bhabha Fund on Agri-waste Materials (EP/P026206/1) 2017-19, GBP323,750

4. Details of the impact

The research has influenced professional practice, underpinned development of new technology and expert systems, and led to the successful commercialisation of materials. In turn, these benefits have improved the health and safety of concrete bridges for those managing their maintenance and the general public who use them.

1. Economic, Professional and Public Services Impact of Bridge Maintenance

Expert Systems – Improved inspection and reporting, increased income and job creation.

Developed through collaborative research undertaken with SHU, the bridge management expert system, licensed to *AMX Solutions Ltd*, has become highly successful in the UK and overseas. Between 2014 and 2020, the AMX Asset Management eXpert system has been used to manage the assets of 45 local authorities in England and Wales, Portsmouth International port, Port of Tyne, M6 toll, Natural Resources Wales (originally Environmental Agency of Wales), Scottish Canals (originally British Waterways), Isle of Man Government, Government of Cyprus (Road authorities), Qatar (Ashgall), Departments of Transport in Dubai, Oman, Albania, Malaysia (2nd Panang crossing, 24km bridge), and two clients in the USA (**E1**).

The *AMX Solutions Ltd*. system reduced bridge inspection time by 20% whilst improving speed, accuracy and detail of inspection data and reports for clients. It provided easy access on site and office to all records of clients' infrastructure, digitally stored in one location (**E1**).

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The annual income of *AMX Solutions* has risen steadily [text removed for publication] Mangat trained both the original KTP Associate and industry supervisor, who now operate *AMX Solutions* as Director and Managing Director, respectively.

Managing Director AMX Solutions Ltd (E1): “*Research Engineers Europe Ltd. participated in concrete repair research projects including developing expert systems led by the Centre for Infrastructure Management at Sheffield Hallam University from 2000 to 2005. I, as their senior engineer, represented the company on the project. The research output inspired me to develop and market a bridge management system after the research projects were completed.... AMX solutions Ltd became commercially established by 2014.... The company has also participated in delivering the bridge inspector training program of the research team at Sheffield Hallam University by introducing the expert system*”.

Training on Professionals and Public Services – increased investment in training, improved maintenance costs, planning for Scottish Government and improved public confidence in the safety of bridges.

Research at Sheffield Hallam into bridge management systems, along with the expertise in materials engineering has informed the development of a comprehensive training programme which has been delivered by the CIM team since 2014. The SHU training forms the core content of the Bridge Inspector Certification Scheme operated by Lantra on behalf of the UK Bridges Board and the Irish National Roads Authority (www.lantra.co.uk/bridge-inspectors). The course is supported by the Department of Transport (DfT) and the Bridge Owners Forum and is mandatory for professional registration (E2).

Since 2014, the CIM team have delivered 1,507 days of bridge inspection competence training to 251 delegates from local authorities across the U.K., trunk roads agencies, area networks, river Tay Road bridge authority in Scotland, Highways England and Qatar Government (E3, E4). These bridge authorities have invested approximately GBP1,300,000 (including staff costs during training). The impacts of the training indicated from feedback received match the objectives stated in the *Management of Highways Structures Code (2005)* and Lantra BICS scheme (2016) (E2). The manager of the Tay Road Bridge (which carries over 28,000 vehicles per day and is strategically important to the economy in the east of Scotland) reports that the CIM bridge inspector training has enabled robust capital spend plans to be agreed with the Scottish Government for future maintenance works; enabled in-house team to carry out repairs thus avoiding unnecessary disruption to bridge users and demonstrated to the public that they can feel confident in using the Tay Road Bridge (E3).

2. Economic, Environmental and Social (health and safety) Impact of AACM (alkali activated cementitious material) concrete

The underpinning research has led to impact in materials for concrete repair and restoration together with fire resistant products for buildings. Licenses were signed for repair and restoration outputs with *C-Probe Systems Ltd*, and fire-resistant elements with *Liquid Granite Ltd*. The Standard BSI PAS 8820:2016, essential for commercialising AACM concrete, was published in 2016 with Paul Lambert as co-author and *C-Probe Ltd* on the steering committee.

C-Probe

C-Probe Ltd. supplies AACM based repair mortars and dual function anode systems for cathodic protection applications and holds a licence from Sheffield Hallam for a customised version of AACM (E5) The AACM matrix distributes the corrosion protection current whilst providing greater acid resistance and strength to the dual function anode. Its ease of application facilitates efficient installation, reduces labour requirements and costs, whilst providing H&S benefits (E7). Based on the SHU research, *C-Probe* established a green manufacturing facility for AACMs to BSI

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PAS8820:2016 at St Helens, [text removed for publication]. The AACMs are utilised for galvanic, hybrid and impressed current anode applications for corrosion protection to recognised standards, EN1504 and ISO12696:2012, and for repair, restoration and strengthening of structures with low whole life impact (**E5**).

[text removed for publication]. *C-Probe* has also carried out trials for potential clients such as HS2, Anglian, Yorkshire and United Utilities.

Liquid Granite

Liquid Granite Ltd developed low carbon impact, high performance, fire resistant, AACM concrete lintels with *King Stone Products Ltd*. These Super Fire Rated concrete lintels based on SHU research achieve a market-leading 240-minute fire rating (double the competitor product rating) without requiring a chemical protective coating which is a H&S hazard on site (**E6**). [text removed for publication].

3. Economic and Professional Impact on *Mott MacDonald*

The research has enhanced the professional capability and competitiveness of *Mott MacDonald Consulting Engineers* in the optimisation of CP system design for structures and corrosion remediation using AACM based anodes. The innovation in CP systems has enabled *Mott MacDonald* to remain ahead of international competition, [text removed for publication], and winning international awards from the *Futures Industry Association* for sustainability and social benefit and from the *International Concrete Repair Institute* for the design and installation of a CP system using AACM mortar anodes for the Commerce Trust Building, Kansas City, USA in 2014 (**E7**)

5. Sources to corroborate the impact

- E1. AMX Solution Ltd:** Company website <https://www.amxsolutions.co.uk/>; <https://www.assetmanagementexpert.com/bridge-management-system> and statement from Managing Director corroborating sales figures.
- E2. Lantra Bridge Inspector Certification Scheme:** Interim Advice Note 192/16 Structures Inspector Competencies and Certification;
IAN 192: <https://www.lantra.co.uk/sites/default/files/2018-07/IAN%20192-16.pdf>;
TSIA 46_16: https://www.lantra.co.uk/sites/default/files/2018-07/TSIA%2046_16%20-%20Structures%20Inspector%20Competencies%20and%20Certification.pdf
- E3. Impact of Bridge Inspector Training** – statements from bridge authorities (Scots Bridges; Fife RC; DOT Wales; and Tay Road Bridge).
- E4. Delivery of Bridge Inspector Training:** Training delivery and delegate records from SHU.
- E5. C-Probe:** company website <https://www.c-probe.co.uk/>; statement from Managing Director, C-Probe Ltd.
- E6. Liquid Granite Ltd:** Statement from Managing Director, Liquid Granite; company website, Kingstone: <http://www.kingstonelintels.co.uk/>; Liquid Granite online coverage: <http://docshare01.docshare.tips/files/19201/192014857.pdf>; <https://idsnmow.blogspot.com/2013/10/liquid-granite-joanne-wong.html>; <http://allsmartbuzz.blogspot.com/2014/01/liquid-granite-ground-breaking-solution.html>
- E7. Mott MacDonald:** Statements from Head of Materials and Corrosion Technology, Mott MacDonald.