Institution: Sheffield Hallam University

Unit of Assessment: 13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: Technologies, Repair Solutions, Management Strategies and Materials for Concrete Infrastructure

1. Summary of the impact

Over a period of 20 years, Professor Mangat and colleagues in the Materials and Engineering Research Institute's (MERI's) Centre for Infrastructure Management have developed significant expertise of concrete materials and structures related to deterioration, repair and maintenance of infrastructure. This body of research has led to **professional practice** and **economic** impacts related to repair selection, asset management systems, curing systems and novel repair/building materials. Mangat's expertise in concrete deterioration, its remediation and repair has been developed into commercial software systems for bridge and asset management and the national, professionally accredited training course for bridge inspectors/engineers. In the REF impact period, bridge management software has been adopted by over 30 UK local authorities and training delivered to 392 bridge management professionals. Commercialisation of two of Mangat's research innovations, alkali activated materials (AAMs) and low voltage accelerated curing systems (LOVACS), has achieved direct sales of £0.5m and development of the spin-out *Liquid Granite Ltd*. Additionally, his corrosion protection systems have been adopted by engineering consultants *Mott MacDonald*, enabling them to win commissioned corrosion-remediation works of over £1m

2. Underpinning research

Mangat joined SHU in 1993 (from University of Aberdeen) as Professor. He has been submitted by SHU for the last three RAEs and is submitted to REF2014 as Category A. In 1993 he brought with him an EC-funded project [i] on expert systems for performance assessment and optimum inspection and maintenance strategies for concrete structures. This was subsequently advanced at SHU by research into the long term performance of concrete repair in highway structures [ii]. The key research developments from this work were: models for long-term deterioration processes in reinforced concrete, particularly chloride diffusion and reinforcement corrosion [1]; equations for the prediction of long-term residual strength and stiffness of corroding members [2]; and methods for characterising the interaction between repair patches and substrate concrete in terms of material properties and repair methods [3].

Mangat's research on deterioration remediation of concrete subsequently diversified into corrosion protection (CP) systems, which he developed with Dr Paul Lambert, Technical Director of Mott MacDonald and, since 2005, Visiting Professor at SHU. Collaborative research between Mangat and Lambert, supported by a Royal Society Industrial Fellowship to Lambert [iii], initially concentrated on numerical modelling of CP systems and their experimental verification. This led to development of optimum CP system designs for corroding reinforced concrete and steel framed masonry structures [4].

Having established expertise in concrete deterioration and repair, Mangat was well placed to identify the limitations of concrete repair materials and the inefficiency of site curing methods with respect to the durability of repair. This triggered the research that led to his development of alkali activated materials (AAMs) and low voltage accelerated curing system (LOVACS).

Research on AAMs, was conducted between 1995 and 2004, supported by EU funding [iv]. Initial research identified the principle of using inorganic alkali material to activate waste-derived reactive powders, thereby avoiding use of high CO_2-producing hydraulic cement. Subsequent experimental investigations determined chemically optimised compositions of multiple reactive powders, filler and activator [5], so characterising the key parameters governing properties such as strength and durability. Further work developed admixtures capable of giving control over AAM 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. Subsequent industrially-sponsored research [v] determined methodologies by which to exploit the excellent adhesive properties of AAMs to achieve dual function anode systems which offer both CP and structural strengthening to concrete structures. AAMs proved to be fire resistant at temperatures exceeding 1100°C, significantly out-performing cement-based or polymer-modified materials. The former typically explode when heated towards 400°C. As described in **section 4**, research

publications on AAMs were restricted in order to protect IP related to this finding.

LOVACS, a novel conductive polymer technology, comprises a flexible polymer-coated textile membrane which, when appropriately incorporated, provides accelerated and efficient curing to in-situ repairs and to concrete construction in general, especially in cold weather. LOVACS was initiated through a Teaching Company Scheme (TCS) awarded to *Inditherm Plc* and Mangat's group at SHU in 2003, subsequent work being supported by EPSRC [vi] and EU grants [vii]. The research that underpins LOVACS started with the development of basic relationships between the composition/thickness of the conductive polymer coating, the size and spacing between electric rails and the optimum size of the polymeric heating element. Subsequently, relationships between power input, the arrangement of the polymeric heating elements (in parallel, series, with or without common middle rail), and the heat output were determined, leading to optimisation of curing system designs for a range of specifications. For example, generic relationships were derived by determining the performance of polymer blankets with different power ratings and configurations on the curing efficiency of concrete elements and repair patches. From these, it proved possible to optimise the LOVACS curing parameters (power, temperature, time) for production of a range of durable cured materials and components. On the basis of this discovery, an international patent [6] was granted in 2005 to Mangat and Catley (the TCS associate) who went on to achieve a PhD (2009). Mangat's research activity in this field continues through an EU grant to improve the quality of concrete repairs using a novel accelerated microwave curing system [viii].

3. References to the research

[1] Mangat, P.S., and Limbachiya, M.C., "Repair material properties for effective structural application" *Cement and Concrete Research* **27**, 601 (1997)
DOI: 10.1016/S0008-8846(97)00027-6 13 Citations (WoS Sept 2013)

[2] Mangat, P.S., and Elgarf, M.S., "Bond characteristics of corroding reinforcement in concrete beams" *Materials and Structures* **32**, 89 (1999)
DOI: 10.1007/BF02479434 36 Citations (WoS Sept 2013)
KEY REFERENCE

[3] Mangat, P.S., and O'Flaherty, F. J., "Influence of Elastic Modulus on Stress Redistribution and Cracking in Repair Patches" *Cement and Concrete Research* **30**, 125 (2000)
DOI: 10.1016/S0008-8846(99)00217-3 25 Citations (WoS Sept 2013)
KEY REFERENCE

[4] Lambert, P., Mangat, P.S., O'Flaherty, F.J. and Wu, Y.Y., "Cathodic Protection of Steel Framed Masonry Structures - Experimental and Numerical Studies", *Materials and Structures* **41**, 301 (2008)
DOI: 10.1617/s11527-007-9240-2 1 Citation (WoS Sept 2013)
KEY REFERENCE

[5] 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)
DOI: 10.1680/coma.2006.159.3.119 1 Citation (Google Scholar Sept 2013)

[6] Mangat, P.S., and Catley, D.G., International Patent Application "Heating Surfaces" Patent No. WO/2005/036930. www.google.co.uk/patents/WO2005036930A1?cl=en

[i] EC Brite Euram grant BREU P3091, PI Mangat "Assessment of Performance and Optimum strategies for the Inspection and maintenance of Concrete Structures using Reliability based Expert Systems" (1992-95)

[ii] Department of Transport grant, LINK Programme, Contract TIO-49, PI Mangat "Long term performance of Concrete Repair in Highway Structures" £221,860 (1993-97)

[iii] Royal Society Industrial Fellowship to Lambert "Novel Electrochemical Solutions for corroding Steel Framed Masonry Heritage Structures" £93,000 (2001–05)

[iv] EU Copernicus programme grants CIPA CT94-0178, PI Mangat "Recycling Fly Ash for Producing Building and Construction Materials Based on a new Mineral Binder system" €87,500 (1995-97). and IC15-CT96-0741, PI Mangat "High Performance Materials Derived from Industrial Waste Gypsum" €54,010 (1997-99)

[v] C-Probe Ltd, PI Mangat "Dual Function, corrosion protection and structural strengthening, CP system for reinforced concrete" £27,112 (2010-13)

[vi] EPSRC, contribution from SHU CTA grant to studentship supervised by Mangat, £75,178 (2005-07)

[vii] EU grant COOP-CT05-016374, PI Mangat "Development of Low Voltage Accelerated Curing Systems for Concrete" €856,046 (2005-07)
[viii] EU grant 605664, PI Mangat "MCure" £347,603 (2013-15)
[ix] Department of the Environment grant, LINK IST-033 DPU 96/64/84, PI Mangat "An Expert System for Optimal Repair in Reinforced Concrete Highway Bridges" £341,623 (1998-2001)
[x] Teaching Company Scheme 3739, PI Mangat "Prototype of Bridge Management software" £68,120 (2001-04)

4. Details of the impact

Mangat's impacts can be characterised as: **influencing professional practice**, through software and training; **economic impact**, through licencing of innovative construction materials and a curing method; and **economic impact** through enhancements to a provider's capability.

Influencing professional practice, through software and training

Software: By the culmination of the project [ii] described in **section 2**, the LINK consortium and its steering group had identified the need for bridge management software including the optimum repair capability for bridge managers. The software house, *Research Engineers Ltd*, was therefore inducted into the consortium and, in 1998, a further LINK project was initiated [ix] to develop an expert system for optimal repair in reinforced concrete highway bridges. This fed into the development of the commercial bridge management software via a TCS [x]. *Infrastructure Asset Management (IAM) Ltd* [A,B] was established in 2004 to commercialise the resultant software, under licence to SHU. The software implements the models and equations from Mangat's research (e.g. refs [1-3]) and uses these, alongside relevant asset design and construction parameters, to determine optimum maintenance, inspection and repair cycles [B]. *IAM* has now become a leading provider of infrastructure asset management software and consultancy. Its *Bridge Management Xpert (BMX)* system is the market standard for bridge management in the UK, with a client base including over 30 local authorities. The more recent *Asset Management Xpert (AMX)* system supports the management of any type of asset. The company has achieved sales of ~£300k in the REF impact period, with ongoing sales of ~ £100k pa.

Training: Mangat's expertise of repair, maintenance and management of bridges has also been intrinsic to the development of a professionally accredited course for training bridge inspectors/engineers to achieve the enhanced competences required by the UK Bridges Board [C]. In 2012, the Department of Transport (DoT) adopted this Bridge Inspection Competence and Training Scheme for the training of all present and future bridge inspectors in the UK [D]. Mangat's contribution was fundamental to the development of this training scheme. Its content was first considered in 2008 when, on the basis of his research record, he was commissioned by the Scots Bridges Group to develop a training course on bridge management and inspection [D]. This was delivered to 85 bridge professionals in Dundee in 2008. Further iterations of the training were subsequently delivered in other locations (London, Birmingham, Dundee, Glasgow, Sheffield, Durham), 11 deliveries yielding a total attendance of 392 bridge inspection and bridge management professionals from local authorities, national authorities (e.g. the Forth Bridge authority), and private sector consultant engineers.

In the light of his lead in the area, Mangat was the only academic consulted when, in 2008-9, the UK Bridges Board undertook a review of bridge inspection competence and training (see section 9.1 of [E]). The recommendations of this review led directly to the DoT Training Scheme. Mangat and his colleagues (O'Flaherty and Lambert) are registered training providers and assessors [F]. O'Flaherty has been submitted to REF in UoA16. This training, together with the software and service impact described above, provide uniformity of bridge condition assessment across the UK, leading to efficient targeted investment by Government and national asset management agencies (e.g., National Rail).

Economic impact through licencing of innovative construction materials and methods

The materials systems and curing approaches developed by Mangat to overcome limitations of conventional repair have also achieved impact. AAMs have been successfully licenced to two companies, *Liquid Granite Ltd* and *C-Probe Systems Ltd*, whilst LOVACS, developed in collaboration with *Inditherm Plc*, has been employed in a number of constructions, such as the Heathrow Terminal 5 Car Park.

AAMs: The Research and Innovation Office (RIO) at SHU worked closely with Mangat to manage and commercialise the IP in AAMs. This led to a decision to exploit AAMs through a spin out company, *Liquid Granite Ltd* [G], rather than publish detailed research findings in the open

literature. Publication would have risked disclosing the optimum compositions needed for commercialisation – policing of IP within the construction industry is impractical. Technology transfer officers in RIO handled all negotiations in the establishment of *Liquid Granite Ltd*, drafting licence agreements and providing authorisation for signature. Market analysis performed by RIO also highlighted the future potential of AAM technology. Ongoing usage of Portland cement is not sustainable due to the volume of CO_2 produced in its manufacture, so the construction industry is increasingly employing low carbon products such as AAMs.

Liquid Granite Ltd [G] was launched in 2006 (licence arrangements agreed 2007) to exploit AAMs. In this case SHU opted to take a licence agreement rather than an equity stake. Equity is held by a business angel plus two commercial partners, *Church Holdings Ltd* and *North Barnsley Partnership* who have collectively invested over ~£50k in cash and at least an equivalent in-kind contribution. *Liquid Granite* concentrates on fire retarding applications, selling AAM-based precast lintels meeting the highest fire resistance specification for fire plug applications in buildings – total sales in the REF period are £109k (licence income £5,455), including a batch of AAM lintels installed in 2012 Olympic village.

In 2012, *C-Probe Ltd* [H] took up a licence from SHU for a customised version of AAMs, concentrating on repair and corrosion protection of reinforced concrete structures. This is based on the electrically conducting version of AAMs and targeted at CP applications [4], consistent with C-Probe's other activities in the corrosion protection business and the supply/installation of CP systems. The customised version of AAM was trialled at Leeds Civic Hall (limestone clad steel framed building), pending a contract exceeding £100k.

LOVACS: The largest order achieved to date for LOVACS was by *Laing O'Rourke* to cure concrete during the Heathrow Terminal 5 construction. To July 2013, *Inditherm*, had achieved total sales of £262,165 [J], of which £35k (licence income £853) fell in the REF impact window. Impetus for further impact was provided by a 2013 research grant to Mangat, within an EU consortium [viii].

Economic impact through enhancements to a provider's capability

Lambert's collaboration with the research of Mangat and O'Flaherty has improved the international competitiveness of *Mott MacDonald* (Lambert's employer). The underpinning research on CP systems has made *Mott MacDonald* a leading international provider of durability enhancement and corrosion remediation solutions to the built infrastructure sector [K]. Examples include advances in the design of CP systems which have been implemented in consultancy projects and the development of a new dual function anode system for CP [L]. Commercial projects resulting from this within the REF impact window include: 85 Fleet Street, London - CP to limestone clad steel framed building, 2008 (value £800k); St James Buildings, Manchester - CP to limestone and glazed brick clad steel framed building, 2008 (value £100k); 992 Walnut Street, Kansas City, USA - Carbon fibre/AAM, CP design for granite clad steel framed portal, 2013 (value $80k); Severn Bridge main suspension cables – residual life assessment (fees £50k); Civic Hall, Leeds, trial carbon fibre/AAM, CP installation to limestone clad steel framed building, 2013 (potential value >£100k); Battersea Power Station – CP design optimisation (prospective fees £20k).

Because these works focus on extending service life and avoiding demolition/reconstruction, each represents an overall cost saving of tens of millions of pounds to clients and wider society.

5. Sources to corroborate the impact

[A] http://www.iamtech.co.uk
[B] Managing Director of *IAM Ltd*, corroborating source 1
[C] http://www.ukroadsliaisongroup.org/en/UKRLG-and-boards/uk-bridges-board/bridge-inspector-training.cfm
[D] Group Chairman, *Scots Bridges Group*, corroborating source 2
[E] Page 108 plus further mentions in UK Bridges Board, Final Report http://www.bridgeforum.org/bof/projects/bict/Bridge%20Inspector%20Training%20and%20Competence%20Phase%201%20Report%20Final.pdf
[F] http://www.shu.ac.uk/research/meri/bridge-inspection-competence-and-training-phase-2
[G] www.liquidgranite.co.uk
[H] Managing Director of *C-Probe Ltd*, corroborating source 3
[J] Managing Director of *Inditherm Plc*, corroborating source 4
[K] http://www.buildings.mottmac.com/materialsandcorrosion/
[L] Managing Director - Western Division, *Mott MacDonald*, corroborating source 5