Institution: Queen's University Belfast

Unit of Assessment: 14 Civil and Construction Engineering

Title of case study:
Assurance of Durable Concrete Structures Using Novel Testing Technologies Developed at QUB

1. Summary of the impact (indicative maximum 100 words)

By ensuring the durability of notable concrete structures in China, such as the Bird's Nest National Stadium Beijing, Dayawan Nuclear Power Station, Harbin-Dalian Railway Bridges, Qingdao Bay Bridge and Beijing-Tianjin Railway Bridges using Autoclam Permeability System and Permit Ion Migration test, developed by Queen's University Belfast (QUB) and sold by a QUB spin-out Amphora Non-destructive Testing Ltd., the savings in future repair costs are estimated to be hundreds of millions of Chinese Yuan (RMB) (the repair expenditure for the three-year period 2009-'11 was RMB 10.2 billion).

Research on permeability and diffusivity testing of concrete on site since 1993 has led to the incorporation of both the Autoclam and the Permit in a corporation standard issued by the Central Research Institute of Building and Construction (CRIBC), China and the test protocol of Permit in a Chinese railway standard.

The training of construction professionals (including more than 200 senior managers from the Chinese construction industry) since 2008 has impacted on improved sales of Autoclam Permeability System and Permit Ion Migration Test, securing around £500k commercial income, and generating new employment in the UK. Since 2008 these test instruments have been sold to 12 countries.

2. Underpinning research (indicative maximum 500 words)

Research on the durability of concrete structures has received global attention since 1980s due to their premature failure and consequential large spend of the construction budget (more than 50% in developed countries) on repair and rehabilitation projects. By mid-1980s it was realised that concrete structures deteriorate due to the ingress of aggressive elements from the service environment into the concrete, primarily governed by its transport properties (viz. sorptivity, diffusivity and permeability), and consequential physical and chemical actions in concrete. Therefore, as highlighted in the Concrete Society Technical Report 31, methods of measuring the transport properties of concrete received global attention. It was also recognised that the choice of test should reflect the predominant degradation mechanism acting on the concrete structure. Therefore, for an offshore structure, an absorption (sorptivity) type test would be suitable for studying the long-term performance of concrete in the tidal zone, whereas a diffusion type and/or pressure differential water permeability type test would be more appropriate for investigating the behaviour of concrete subjected to deep submersion. By following this rationale, the **Autoclam Permeability System** [grant (i); Basheer et al., 1995] and **Permit Ion Migration Test** [grant (ii); Basheer et al., 2005] were developed so as to obtain an index of the relevant transport properties in order to assess the durability of concrete at different exposure conditions.

The protocols for carrying out the *in situ* air permeability test, water permeability test and water absorption test on concrete and stone masonry structures using the Autoclam Permeability System were developed since 1993 by **Basheer, Long** and **Montgomery** (left QUB in 2003) [Basheer et al., 1994; 1995; Basheer and Nolan, 2001], supported by an SERC grant [grant (i)].

The Permit Ion Migration test protocol [Basheer et al., 2005] for measuring the resistance of concrete to chloride ion diffusion was developed by **Basheer**, **Robinson** and **Long**, through funding from EPSRC [grant (ii)]. **Nanukuttan** and **Basheer** compared the Permit test with lab-based chloride diffusion tests, in a project funded by the European Commission [grant (iii)] and the results were published in a book by Spon Press [Tang et al., 2012]. The uniqueness and quality of this research received international awards:

(i) The **ACI/James Instruments Best Non-destructive Test Award,** USA in 1998.

(ii) **Best paper award for university-based research** at Structural Faults and Repair-03

international conference in London, 2003.

(iii) **Best student paper award** at the international conference in Cape Town, November, South Africa, 2004.

Meanwhile, as part of an EPSRC International Travel Grant [grant (iv)] awarded to **Long** and **Basheer**, the premature deterioration of concrete structures in China due to poor quality construction was identified. The devastation caused by the earthquake in Sichuan, South West of China in 2008 due to the collapse of concrete bridges and buildings is an example of this. Realising the benefit of an early assessment of the durability of their concrete structures, a research programme was initiated, supported by EPSRC [UK-China Bridge in Sustainable Energy and Built Environment grant, grant (v)] to validate QUB tests for Chinese constructions. The following sub-contracts were completed as part of this project:

(i) 'Establishment of correlations between the Autoclam method and the permeability test methods specified in China standards', by CRIBC, Beijing.

(ii) 'Research on the correlation of PERMIT ion migration test and related Chinese standards', Department of Civil Engineering, Tsinghua University, Beijing.

As a consequence, both the Autoclam and the Permit were established in China for the quality assurance of their concrete structures, providing a platform for the subsequent development of related Chinese Standards.

3. References to the research (indicative maximum of six references)

Research Outputs

References identified by an asterisk are suggestions for assessing the research quality.

1) Basheer, P.A.M., Long, A.E. and Montgomery, F.R. (**1994**, July/August), "The Autoclam - a new test for permeability", Concrete, The Concrete Society, 28 (4), pp 27-29.

***2)** Basheer, P.A.M., Montgomery, F.R. and Long, A.E. (**1995**), "'CLAM' tests for measuring in-situ permeation properties of concrete", Non-destructive Testing and Evaluation International, 12, pp 53-73; DOI: 10.1080/10589759508952835.

***3)** Basheer, P.A.M. and Nolan, E. (**2001**), "Near-surface moisture gradients and in situ permeation tests", Construction and Building Materials, 15 (2), pp 105-114; DOI: 10.1016/S0950-0618(00)00059-3.

***4)** Basheer, P.A.M., Andrews, R.J., Robinson, D.J. and Long, A.E. (**2005**), "'PERMIT' ion migration test for measuring the chloride ion transport of concrete on site", Non-destructive Testing and Evaluation International, 38, pp 219-229; DOI: 10.1016/j.ndteint.2004.06.013.

5) Tang, L., Nilsson, L-O. and Basheer, P.A.M. (**2012**), "Resistance of concrete to chloride ingress: Testing and modelling", Spon Press, 241 pp. ISBN 978-0-415-48614-9.

Research Grants

(i) Assessment of the effectiveness of methods used to improve the surface durability of concrete, SERC grant GR/H41003/01 (**Apr. 1992-Jul. 1996, £95,020** non-FEC grant) to AE Long, FR Montgomery, and PAM Basheer.

(ii) Development and validation of an in-situ accelerated ionic migration test, EPSRC grant GR/L26308/01 (**Apr. 1997-Mar. 2000, £164,625** non-FEC grant) to PAM Basheer, DJ Robinson and AE Long.

(iii) ChlorTest: Comparative study of different methods of measuring the chloride penetration resistance of concrete, EU grant GRD1-2002-71808 (**Jan. 2002-Dec. 2005, €1.2million total, QUB grant £41,874**) to L Tang (Sweden), PAM Basheer, SV Nanukuttan and 14 other EU partners.

(iv) Measuring durability properties of near-surface concrete for design and quality control of reinforced concrete structures in China, EP/C519183/1 (**Sep. 2004-Aug. 2005, £3,873**) to AE Long and PAM Basheer.

(v) UK-China Bridge in Sustainable Energy and Built Environment grant, EP/G042594/1 (**Sep. 2009-Aug. 2012, £860,748**); key researchers from Civil Engineering: PAM Basheer and Y Bai (left QUB in 2012). http://www.qub.ac.uk/sites/sciencebridge/

4. Details of the impact (indicative maximum 750 words)

The underpinning research on developing methods to assess the durability of concrete structures *in situ* has led to significant international impact, particularly in China, on change of practice and understanding of procedures, resulting in savings in life cycle cost of concrete structures. A QUB spin-out, Amphora NDT Limited (www.amphorandt.com), was able to increase the volume of sale of Autoclam and Permit, particularly to China, since 2008, as a consequence of the underpinning research described in section 2. That is, the impact was realised in three forms: impact on practitioners and services, impact on economy, and impact on commerce, as described below.

Impact on Practitioners and Services

The research described in section 2 and associated contributions by **Basheer** and **Nanukuttan** (from 2004) to RILEM Committees TC178 on Testing and Modelling Chloride Penetration in Concrete (**2001-'05**) and TC189 on Near Surface Evaluation of Covercrete (**2003-'07**) have resulted in the incorporation of both the Autoclam and Permit in state-of-the-art report documents prepared by RILEM [**sources (i) and (ii)**] and a book by Spon Press [**source (iii)**]. As a consequence, these instruments are used now in 12 countries (USA, Canada, Mexico, Libya, South Africa, Republic of Ireland, United Kingdom, Norway, Kuwait, India, China and Australia) [**source (iv)**] to assess the durability of concrete structures.

The UK-China Science Bridge on Sustainable Energy and Built Environment [Research Grant No. (v) in section 3] was the driver for the impact on practitioners and services in China. The project comprised proof-of-concept testing of the Autoclam and Permit in China, technology transfer activities, training programmes and thematic workshops, in collaboration with the project partners: CRIBC, China Railway Construction Corporation Limited, China State Construction Engineering Corporation, Research Institute of Highway Ministry of Communication, Zhejiang University, Tsinghua University, Shanghai Jiao Tong University, Chongqing University and Xi'An University of Architecture and Technology. Starting with the participation of 30 senior managers from China at a dedicated UK-China Science Bridge conference session at Structural Faults and Repair international conference in Edinburgh in 2010, the technology transfer and training activities continued in 2010, 2011 and 2012. An international workshop on '*in situ* monitoring and assessment of concrete structures' was held at QUB on 19 June 2010, which was attended by 25 delegates from China. On 28 and 29 September 2011, the Research Institute of High Performance Concrete in CRIBC and QUB jointly hosted the first UK-China Innovation Symposium in Beijing, which was attended by 150 invited delegates from the construction sector in China. The professional training activities continued in 2011 when QUB hosted 25 managers from the Chongqing Municipal Commission of Urban-Rural Development from 18 November to 7 December 2011 to demonstrate QUB technology transfer activities in the field of durability of concrete constructions. These training activities concluded by showcasing the QUB devices at the UK Concrete Show in Coventry on 22 and 23 February 2012.

A UK-China Science Bridge Concrete Centre (SBCC) was established in May 2009 at CRIBC to provide professional advice and services on durability of concrete to the Chinese construction industry. Dr Ting-Yu Hao, who is the principal Science Bridge partner in CRIBC, has been instrumental in incorporating Autoclam and Permit in guidance notes and standards for assessing the quality of concrete constructions in China. Dr Hao writes [**source (v)**]: "*Autoclam and Permit were incorporated in a corporation standard issued by CRIBC. On the other hand, a railway standard title with Railway Concrete, TB/T 3275-2011, quoted a test using a similar process of Permit. The corresponding part is Appendix F with a title of Test Method for measuring surface permeability of concrete.*" In the UK, the Highway Agency Standards BA/06 recommends the use of Autoclam for testing and monitoring the condition of concrete structures.

Impact on Economy

The Research Institute of High Performance Concrete (www.chinahpc.net), part of the CRIBC, with Dr Hao as its Deputy Director, is a major accredited testing laboratory for the performance assessment of construction projects, products and materials in China, and has a prestigious third-

party witness testing qualification. Dr Hao and his team have assessed notable structures using Autoclam and Permit in China, including: concrete stands of Bird's Nest Stadium (National stadium for the 29th Olympic Games), several piers and bridges of Beijing-Shanghai high speed rail, Harbin-Dalian high speed rail bridge, Huangjiahe bridge in Guyuan, Ningxia Hui Autonomous Region and concrete containment of Daya Bay Nuclear power plant. With the support from Amphora Non-destructive Testing Limited and QUB, Permit was applied in the construction of Qingdao Bay Bridge in 2008 in China. The Qingdao Bay Bridge was the first bridge built in the cold and frozen seas in north China **[source (vi)]**. The impact of ensuring the durability of these concrete structures by early age testing using the Autoclam and Permit on the economy of the Chinese construction industry can be better understood if some of the national statistics are compared.

In the last two years expenditure in China on new construction and repair and rehabilitation was RMB 16.7 billion and RMB 3.8 billion annually respectively. These figures compare with RMB 6.7 billion and RMB 1.3 billion spent annually in 2005-08 on new construction and repair and rehabilitation respectively. That is, there has been a steady increase in construction budget, but large sums of money were spent on repair and rehabilitation work. Therefore, by ensuring the durability of concrete structures using early age testing, the proportion of money that will be spent on repair is reduced in future years. This was confirmed by Dr Hao, who says: *"By durability assessment, we may have saved millions in the repair work".*

Impact on Commerce

The impact on commerce has been by way of increased sales of Autoclam and Permit, particularly to China, by Amphora NDT Limited [**source (iv)**], a QUB spin out company, which manufactures and markets NDT techniques and sensor systems (www.amphorandt.com). Amphora has sold more than 60 of these products, securing around £500k commercial income since 2008. As a result, it was possible to create two new jobs in the UK.

5. Sources to corroborate the impact (indicative maximum of 10 references)

(i) Non-Destructive Evaluation of the Penetrability and Thickness of the Concrete Cover, State-of-the-Art-Report of RILEM Technical Committee 189-NEC, Report No. 40, RILEM Publications S.A.R.L., Bagneux, France, 2007, ISBN 978-2-35158-054-7.
(ii) Update of the Recommendation of RILEM TC 189-NEC Non-destructive Evaluation of the Concrete Cover, Materials and Structures, Vol. 41, 2008, pp 443-447. DOI 10.1617/s11527-007-9334-x.
(iii) Resistance of concrete to chloride ingress: Testing and modelling, Spon Press, 2012, 241 pp. ISBN 978-0-415-48614-9.
(iv) Amphora NDT Limited, Belfast, Northern Ireland (www.amphorandt.com) - Contact: Chairman, Amphora Board.
(v) Central Research Institute for Buildings and Construction, Beijing, China - Contact: Deputy Director, High Performance Concrete Research Institute.
(vi) Department of Civil Engineering, Tsinghua University, Beijing, China - Contact: Director, Institute of Building Materials.