Multi-scale cementitious self-healing systems and their application in concrete structures

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ABSTRACT: The Materials for Life (M4L) project team have developed multi-scale self-healing systems for cementitious materials using a range of interdisciplinary technologies. The three-year EPSRC funded project, which began in July 2013, is a collaboration between Cardiff University, University of Cambridge and University of Bath. The project has investigated individual healing techniques, combined these techniques in the laboratory and now used these techniques in the field at the full-scale. This paper will summarise the findings and challenges encountered to date.

The individual healing techniques address damage at various length and time scales and include encapsulating healing agents, bacterial healing, crack closure using shape memory polymer (SMP) tendons and vascular networks with the ability to supply healing agents on a repeated basis. Amalgamating these techniques to form a multi-scale healing system has been shown to improve the overall healing efficiency with respect to strength recovery. This work has given an insight into the interaction between the various healing processes and healing trigger mechanisms.

The project's primary industrial sponsor, Costain, have built a full-scale concrete structure, which includes a number of wall panels incorporating different combinations of self-healing techniques. The wall panels are loaded to induce cracks after which the recovery of structural properties is monitored over time. The challenges encountered in scaling-up, the feasibility of construction and early performance results are discussed. These field-scale trials have been an important step in evaluating the feasibility of self-healing concrete.

Keywords: multi-scale; self-healing; concrete; cementitious; site-trials.

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INTRODUCTION

The "Materials for Life (M4L): Biomimetic multi-scale damage immunity for construction materials" project [1] addresses a vision of a sustainable and resilient built environment. The new generation of materials and structures developed will continually monitor, regulate, adapt and repair themselves without the need for external intervention. In this way, such self-healing materials and intelligent structures will significantly enhance durability and serviceability, improve safety and reduce maintenance costs [2].

The conglomerate materials that form the basis of the majority of such construction materials (concrete, grouts, mortars, hydraulically bound materials, grouted soils etc), are extremely complex multiphase composites with multi-scale internal structures that exhibit a hierarchy of multi-dimensional, time-dependent damage mechanisms. For example, in cementitious composites nano-scale damage occurs during hydration and the strength development phase, while medium-term damage due to chemical attack also leads to the formation of defects in its structure. Other short-term factors such as residual stresses that arise during curing and compaction or longer-term physical actions, like repeated cycles of freezing and thawing and fatigue loading, can also produce dislocations at the nano-scale. In time, this nano-damage grows to form micro-cracks within the cement paste and these micro-cracks themselves eventually coalesce to form networks of meso-cracks. It is these meso-scale cracks that lead to debonding between the paste and aggregate particles, a network that finally grows to become the discrete number of visible macro-cracks which so often lead to corrosion of the steel reinforcement.

Cracking is inevitable in reinforced concrete structures, indeed it is an inevitable consequence of its response to thermal effects, early-age shrinkage, mechanical loading, freeze-thaw effects or a combination of these factors [3]. It is widely accepted that the design-life of concrete structures is reduced by the development of micro-cracks which allow the ingress of water, carbon dioxide and chlorine ions into the structure. This causes carbonation, sulphate-related degradation of the concrete and corrosion of the reinforcement. This concrete degradation currently results in the requirement for regular repair and maintenance work to concrete structures, which comes with large associated costs. Hence, it is evident that a system is needed that can act at both the different spatial and temporal scales at which the damage can form. The purpose of this research is to identify a cost effective self-healing cementitious composite.

M4L is a three-year EPSRC funded project which began in July 2013. The project consortium, led by Cardiff University and including the University of Cambridge and the University of Bath, has worked alongside industrial partners to bring together the whole supply chain to address the challenges and feasibility of delivering self-healing materials on civil engineering projects in the future. Individual technologies developed, work done on combining self-healing technologies and construction of the first UK self-healing site trial is presented in this paper.

SELF-HEALING TECHNOLOGIES

The interdisciplinary nature of this project makes use of multi-scale systems that use primarily four main technologies to promote and enable self-healing of construction materials over various timescales. These are: the release of healing agents from microcapsules, the deposition of material in the cracks promoted by bacterial action, crack closure using shape memory polymer tendons, and the repeated supply of healing agents through vascular networks.

Release of healing agents from microcapsules

Led by University of Cambridge, this element of research focused on embedding microcapsules containing various healing agents into a cement based matrix. Upon crack formation, and when the crack front reaches the microcapsules, the rupturing capsules release healing agents into the crack promoting healing. This action serves to block the ingress of harmful substances and aids the recovery of structural strength.

The work focused on the manufacture of microcapsules and the selection of a suitable cargo. Three shell manufacturing techniques were investigated, i) interfacial polymerisation (ii) complex coacervation and (iii) using a microfluidic device. The microcapsule size varied between 50 µm to 700 µm on average, depending on the technique. Minerals were selected as the preferred healing agent and an experimental series using macro-scale glass capsules showed that all mineral compounds improved substantially the condition of cracked specimens [4]. These water soluble minerals were then successfully encapsulated and the production scaled-up. Figure 1 shows microcapsules approximately 600 µm in diameter made from pig gelatine which contain 50% sodium silicate and 50% oil. Detailed analysis and characterisation of the different microencapsulation systems was carried out and the effect the volume fraction of microcapsules in the cement based matrix has on: healing, the fresh and hardened properties of cement based materials was considered [5].

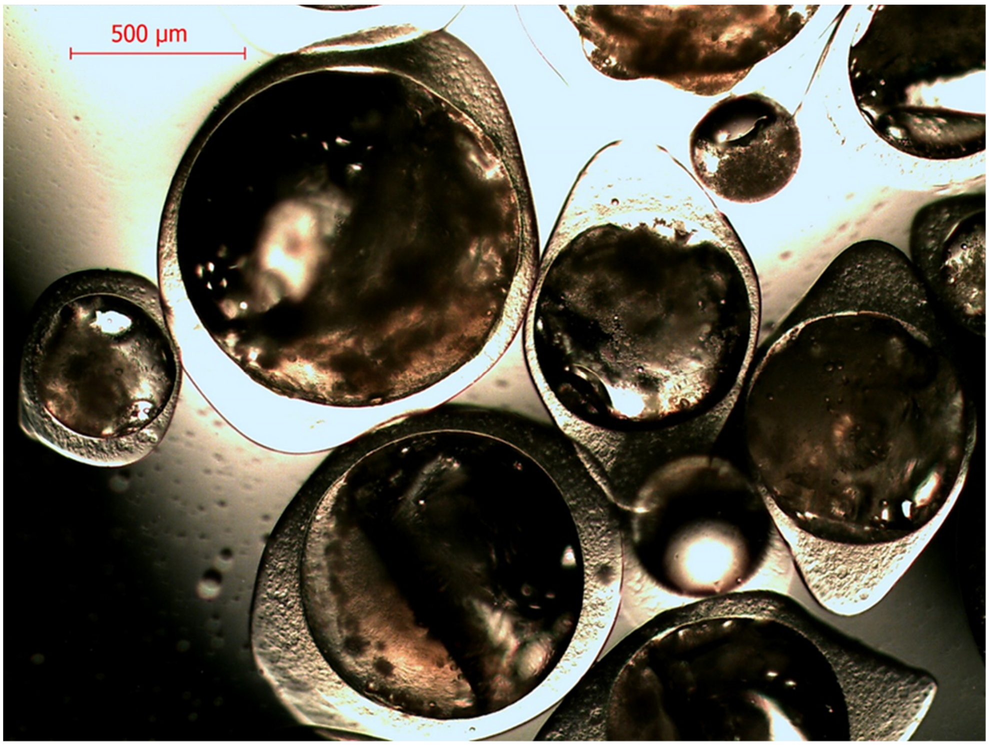

Figure 1: Microcapsules made from pig gelatine and containing 50% sodium silicate and 50% oil (picture courtesy of University of Cambridge)

Deposition of material in the cracks promoted by bacterial action

The University of Bath focused on a bacterial self-healing solution, whereby specially selected bacteria, which can survive in concrete, precipitate calcite in any cracks in concrete. The work involved selection of suitable bacteria that can behave in the necessary way in the extremely hostile environments within concrete. Such considerations led to selecting bacteria that can survive alkaline conditions, form spores, germinate into live bacteria when the conditions are suitable and form calcite. Screening of calcium compounds for calcite production was undertaken and survival of spores under extreme compression was examined [6]. Figure 2 shows magnified calcium carbonate crystals that have been produced by bacteria in-vitro.

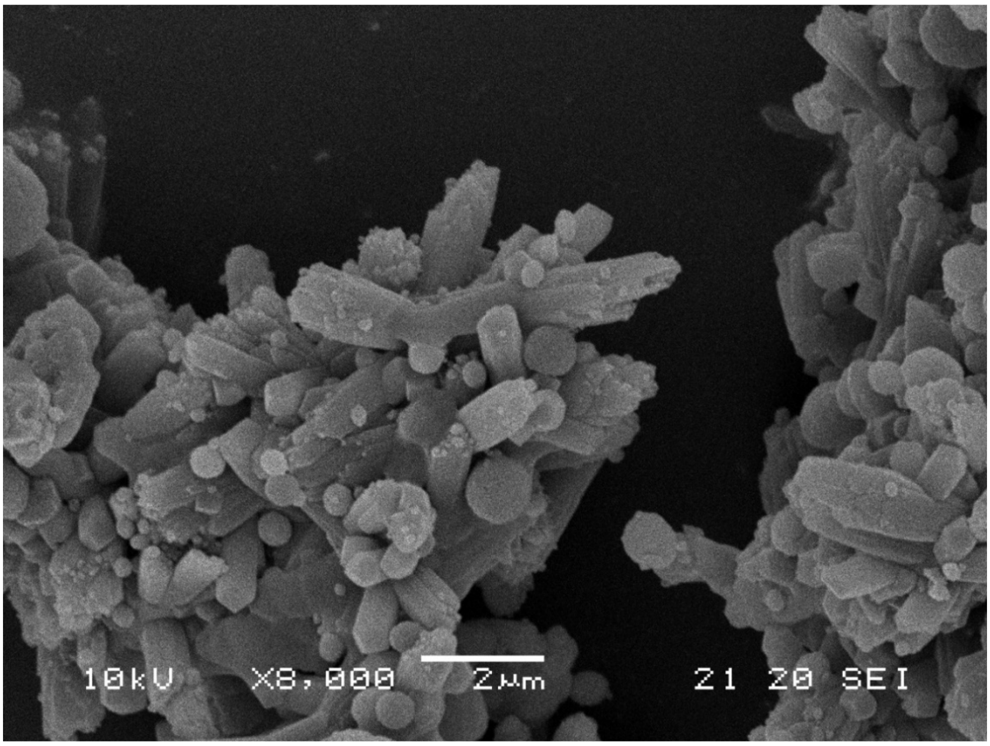

Figure 2: Magnified calcium carbonate crystals the product of bacterial healing (picture courtesy of University of Bath)

Crack closure using shape memory polymer tendons

Cardiff University developed a solution using shape memory polymers (SMP) as a crack closure mechanism within concrete structures to enhance autogenic healing. This follows on from previous research at Cardiff into the use of polyethylene terephthalate (PET) strips for crack closure [7]. The SMP, upon activation, returns to a built-in shape, or if restrained generates an external stress. One of the key challenges in this work was to scale-up the SMP tendons from small 125 mm long mortar beams to firstly 500mm long beams, then to 1m long beams and finally to full scale in the site trials. The tendons, initially developed using PET strips, and then formed from filaments were designed to create 1 MPa compressive stress at the crack face after activation. A schematic of a SMP tendon is shown in Figure 3. A new testing setup and sequence was developed to characterise the SMP, qualitative evidence of healing was sought and load recovery results were generated. Key indicators for developing filaments with higher stress capabilities were identified and reported by Pilegis et.al. [8].

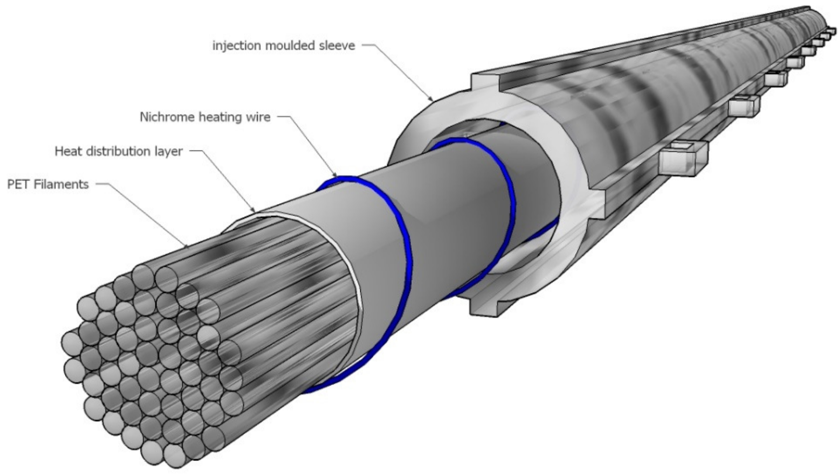

Figure 3: Schematic of a shape memory polymer tendon

Repeated supply of healing agents through vascular networks

Cardiff University has also developed a technique for creating vascular networks within concrete structures. The concept is to create a hollow network that can be re-used over the lifetime of a structure, with the primary aim being to enhance and enable multi-scale healing in cementitious materials. Vascular networks in 1D and 2D were created using 4 mm circular diameter channels in beams, slabs and walls. Characterisation of the different properties which influence the flow of the healing agent have been investigated.

To enable the healing agents to migrate to areas of damage the networks were placed in the areas most susceptible to cracking, which is typically the cover zone of concrete subject to tension. A 2D vascular network of channels can be seen in a 600 mm square slab mould prior to casting in Figure 4. The preferred healing agent was sodium silicate, which combines with sodium hydroxide to form Calcium Silicate Hydrate in the cracks [9]. A key finding of the work was that a pressurised vascular network, with externally supplied healing agent is capable of promoting significant strength recovery. When used in combination with the SMP technique, for example, the strength recovery was shown to double from 15% to 30% in 500mm beams with 0.5mm cracks when supplied with sodium silicate.

Figure 4: Vascular network channels before casting 600mm square 100mm deep slab

SITE TRIALS

One of the aims of the M4L research project was to scale-up from laboratory size and apply these techniques to larger scale concrete structures on a construction site. The design, construction, testing and monitoring of the site structures, are described briefly in this section. The self-healing concrete site trial was built by Costain in October 2015 within the site compound of the A465 Heads of the Valleys section 2 project in South Wales. Costain are the lead contractor on the £200M Welsh Government contract, where 8.1km of existing highway is being upgraded from single to dual carriageway between Gilwern and Brynmawr in South Wales.

Site trial set-up and constituents

A conventional cantilever wall mimicking a retaining wall was used for the trial, replicating many of the permanent work structures on the highway project. A base, reaction wall and 5 individual panels were cast in concrete, as shown in the schematic in Figure 5. The panels are 1.8m in height, 1m wide and 0.15m in depth. Four panels contain different combinations of self-healing techniques, whilst a fifth panel acts as a control. Table 1 shows the contents of each trial panel and Table 2 shows the basic concrete mix that was used with a design strength of C40/50.

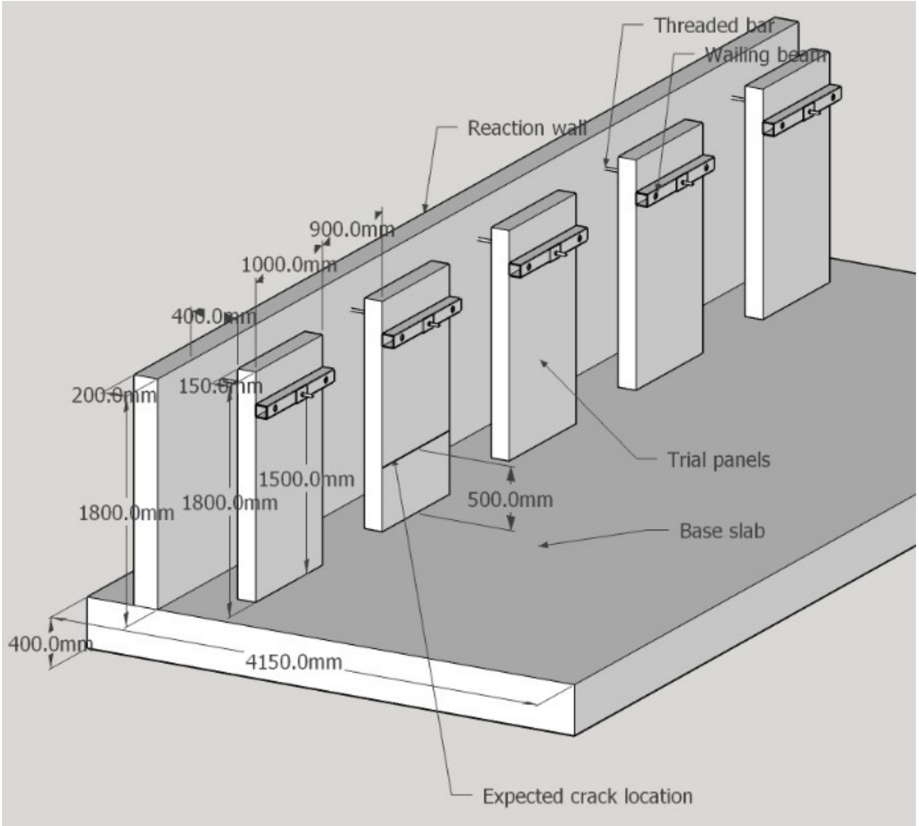

Figure 5: Site trial concept design

Table 1: Trial panel notation and contents

Panel	Contents
A	Microcapsules and basic mix (microcapsules 8% by weight of cement)
B	SMP tendons and flow network with basic mix
C	Encapsulated bacterial spores, nutrients and flow networks with equivalent concrete mix
D	Control using basic mix
E	Control with flow network using basic mix

Table 2: Basic concrete mix design

Material	SSD Quantity (kg/m³ unless noted otherwise)
Cement (CEM I)	415
10mm Limestone aggregates	944
Limestone fines (0-2mm)	396
Marine sand	393
Water	179
Admix: VS100 (SIKA) plasticiser	0.35 l/100kg cement
Admix: SIKATARD R retarder	0.1 l/100kg cement

In Panel A, the microcapsules, illustrated in Figure 1 at 8% by weight of cement, were manually added to the basic concrete mix on site. In Panel B shape memory polymer 'tendons' were tied onto the main reinforcement within the trial structure, these were activated by passing an electrical current through heating wires incorporated in the tendons. A 2D network of 4mm diameter channels was also created using polypropylene tubes, which were removed from the concrete once cured. The tubes were joined using 3D printed joints made from polylactic acid which remained in the wall. The tendons and flow network setup before casting can be seen in Figure 6. In Panel C, the bacteria used was bacillus pseudofirmus, which was infused into lightweight aggregates in the form of perlite. Precursors and nutrients were also included in separate aggregates as a food source for the bacteria. This purpose made bacteria mix with the same design strength as the basic mix was placed in a 500 mm layer at the expected location of the cracking.

Figure 6: Shape memory polymer tendons and vascular network setup before casting concrete

Site trial testing sequence

Controlled damage of the walls was initiated between 33 and 36 days after casting, by applying a load to the top of the cantilevered panels. This was achieved via a spreader beam, threaded bar and jack pulling against the reaction wall. The panels were designed to crack on their front face, 500mm from the base, which allowed the majority of the measuring techniques to be focussed on one area of the panel. The peak load applied to the panels was approximately 24KN which resulted in crack widths on the front surface of the wall of approximately 0.5mm. After the initial loading phase, the tendons in Panel B were activated and a reloading cycle was initiated to assess the effectiveness of the SMP system. Similarly Panel E which was used as a Control for Panel B and was subjected to the same loading and unloading cycle.

Throughout this initial phase of the site trial, the crack width, deflections, strains, permeability and applied loading on the panels were monitored and the results will be compared with a second phase of load testing which is planned for the summer of 2016 when the panels will be 6 months old. The monitoring techniques adopted made use of DEMEC pips, optical microscopes, linear variable displacement transducers (LVDT), load cells, on-site permeability apparatus and a Digital Image Correlation (DIC) system. Following the initial loading, monitoring of the panels was conducted at one month intervals recording microscope images, DEMEC readings and any changes in the LVDT readings. The intention is to flush the flow networks in panels B and E with sodium silicate healing agent 90 days after initial loading.

Site trial initial results

This section will provide a brief insight into the initial loading results of the trial panels. Other results will be published in due course when they become available. One of the aims of the M4L project was to scale-up the self-healing techniques for site trials and this has been successfully achieved as evidenced in Figure 7.

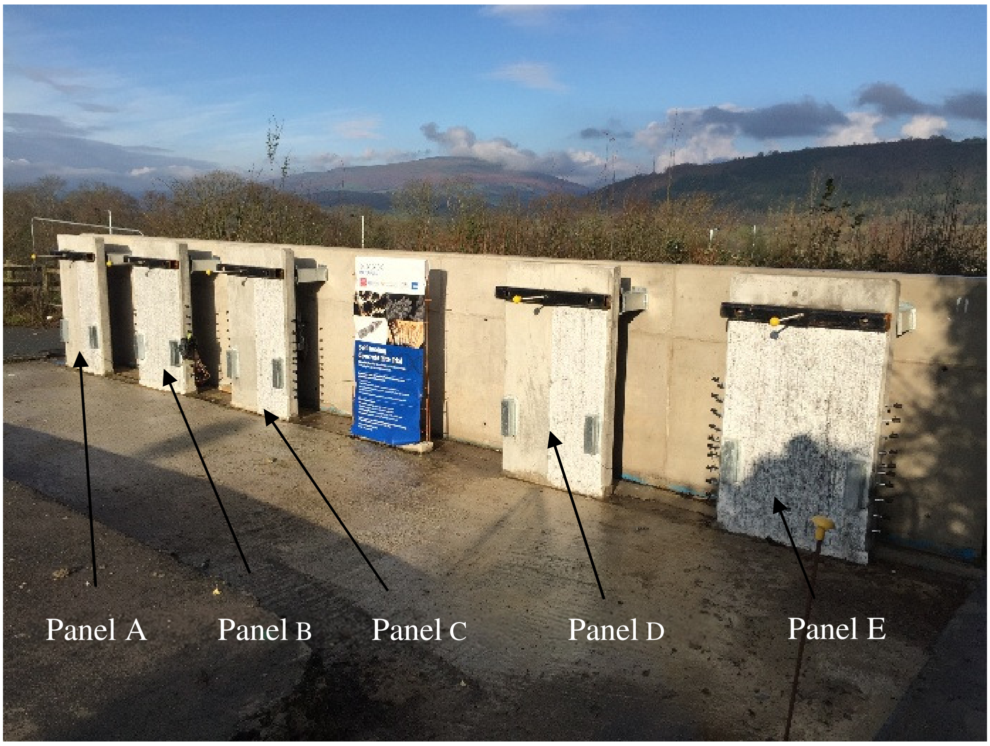

Figure 7: Site trial panels after initial loading

Early visual measurements have shown some crack healing in Panel A when compared with the control Panel D. Mechanical load regain will be assessed upon reloading of the panels at a later stage of the project. The activation of the polymer tendons in Panel B resulted in an average reduction in crack width of around 20% and an increase in stiffness upon reloading of the panel. Panel C has also demonstrated some evidence of crack healing, although further tests are required to assess whether this healing is due to the presence of bacteria or through the autogenous healing process which naturally occurs in concrete structures.

The load versus the displacement curve for the top of all panels from the initial load cycle is shown in Figure 8. During loading, several cracks were formed as can be seen from the load peaks and troughs in the graph. The formation of the final crack at the expected location, approximately 500 mm above the base, was achieved with a load ranging from 20 to 24kN.

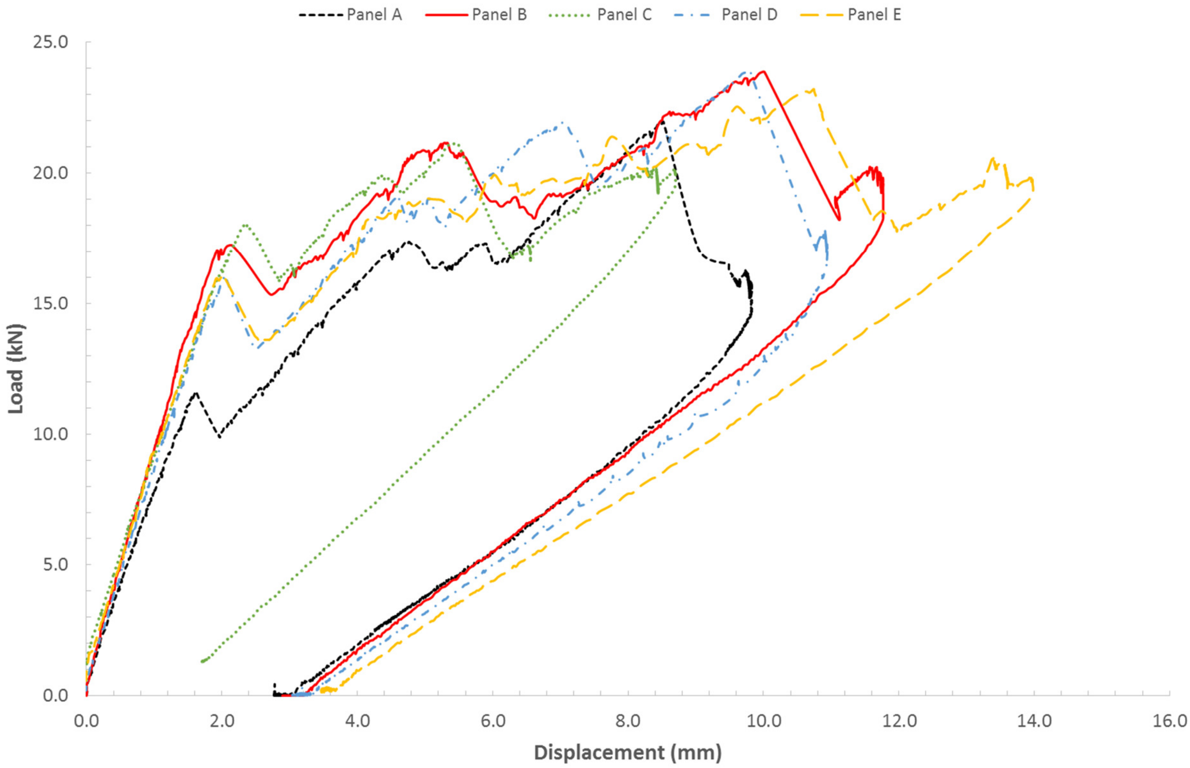

Figure 8: Load versus top of the panel displacement

Figure 9 shows the vertical strain of Panel B after unloading and three cracks can be seen that correspond to the higher peaks in the load displacement graph. The crack at the expected location is wider than the other ones as shown by the DIC in Figure 9. Similar cracking behaviour and the occurrence of the largest crack at 500 mm above the base was observed in all panels.

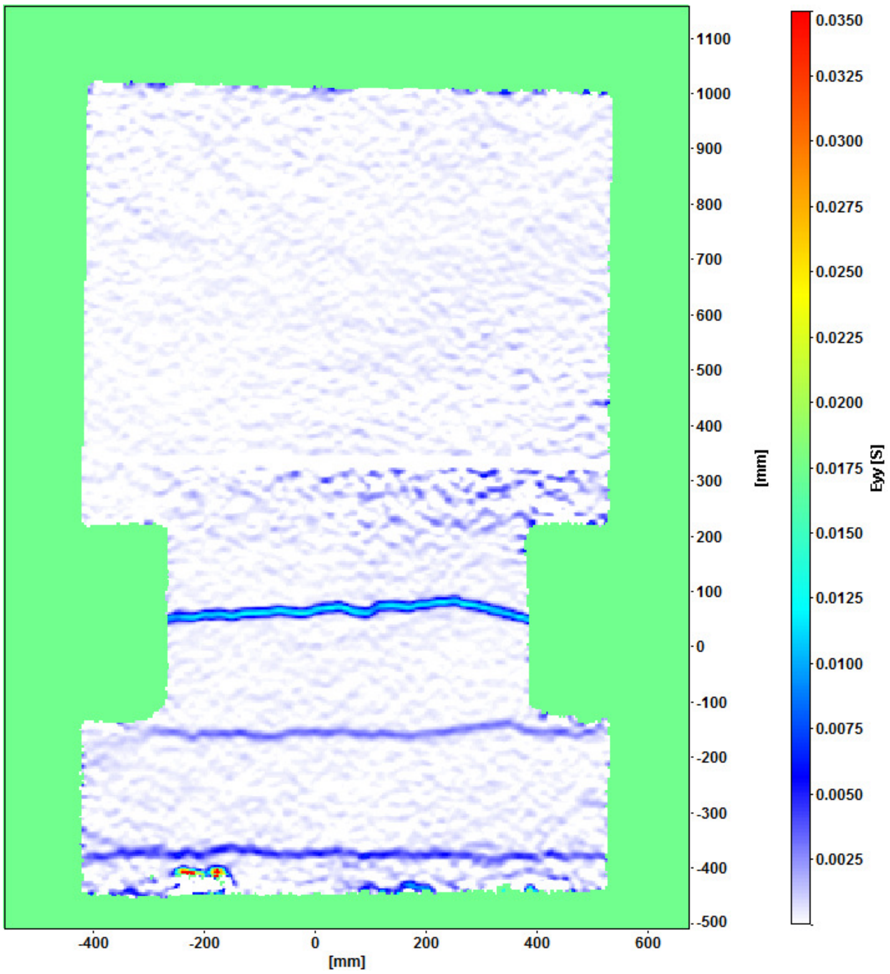

Figure 9: DIC strain plot of Panel B after unloading

The microscope image analysis showed that the residual crack width of the crack 500 mm above the base of all panels ranged from 0.063 mm to 0.161 mm. The site trials are still ongoing and the monitoring is carried out every month as detailed in the testing sequence section. The next site trial event is filling the flow networks with a healing agent and evaluation of the corresponding healing effectiveness. The challenges associated with undertaking these site trials have been significant, but many have been overcome. These included scaling up the techniques, making custom rigs and dealing with inclement weather conditions away from the laboratory. For example, a key requirement for the SMP tendons was the need to develop an electrical activation system. The evaluation of healing will be undertaken after the second phase of load testing which is planned for the summer of 2016.

CONCLUSIONS

The M4L self-healing concrete trials have been successful in achieving their primary aim, which was to scale-up the four individual healing technologies and implement these in a full-scale structure on a construction site. Each technology works at a different length scale and could respond to the range of damage that can arise in construction materials. The physical implementation has been shown to be a relatively straightforward process. Initial results are sufficiently positive to give confidence that these techniques warrant further investigation, working towards reducing and removing the requirement for inspection, maintenance and repair of concrete structures.

Acknowledgements

The writers gratefully acknowledge the financial support for this study given by the Engineering and Physical Sciences Research Council (EPSRC) (Project Ref. EP/K026631/1). Thank you must be extended to the whole Materials for Life project team whose collaboration made this work possible and to Costain for providing construction support and use of their site for the trial. Further information about the M4L project, its collaboration members, academic publications and outreach activities can be found on the project website http://m4l.engineering.cf.ac.uk.

REFERENCES

1. LARK, R.J., AL-TABBAA, A., PAINE, K., *Biomimetic multi-scale damage immunity for construction materials: M4L project overview*, in: ICSHM 2013: Proceedings of the 4th International Conference on Self-Healing Materials, Ghent, Belgium, June 16-20, 2013. Ghent University
2. DE ROOIJ, M. R. VAN TITTELBOOM, K. DE BELIE, N. SCHLANGEN, E. *Self-Healing Phenomena in Cement Based Materials*. State-of-the-Art Report of RILEM TC 221-SHC. 2013.
3. RICHARDSON, M.G., Fundamentals of durable reinforced concrete (Modern Concrete Technology). 2002. Spon Press, London.
4. KANELLOPOULOS A., QURESHI T.S. AND AL-TABBAA A. *Glass encapsulated minerals for self-healing in cement based composites*, Construction and Building Materials, Vol. 98, 2015, pp. 780-791.
5. GIANNAROS P., KANELLOPOULOS A. AND AL-TABBAA A. *Sealing of cracks in cement using microencapsulated sodium silicate*, Smart Materials and Structures, 2016, paper accepted (in-press).
6. SHARMA, T., ALAZHARI, M., COOPER, R., HEATH, A. AND PAINE, K., *The requirements for autonomic microbiologically-induced calcite-precipitation in concrete*. Paper presented at the 5th International Conference on Self-Healing Materials, Durham, USA, June 2015
7. ISAACS, B., LARK, R., JEFFERSON, T., DAVIES, R., DUNN, S., Crack healing of cementitious materials using shrinkable polymer tendons. Structural Concrete. doi:10.1002/suco.201200013, 2013.
8. PILEGIS, M. TEALL, O. HAZELWOOD, T. JEFFERSON, T. GARDNER, D. LARK. R. *Delayed concrete pre-stressing with shape memory tendons*. Fib symposium 2015, Copenhagen, Denmark.
9. DAVIES, R., JEFFERSON, T., LARK, R. GARDNER, D, *A novel 2D vascular network in cementitious materials.* Fib symposium 2015, Copenhagen, Denmark.