Smart Biomimetic Construction Materials for Next Generation Infrastructure

Abir Al-Tabbaa
University of Cambridge

Bob Lark
Cardiff University

Kevin Paine
University of Bath

Tony Jefferson
Cardiff University

Tim Embley
Costain

Abstract (max 500 words)

The resilience of building and civil engineering structures is typically associated with the design of individual elements such that they have sufficient capacity or potential to react in an appropriate manner to adverse events. Traditionally this has been achieved by using 'robust' design procedures that focus on defining safety factors for individual adverse events and providing redundancy. As such, construction materials are designed to meet a prescribed specification; material degradation is viewed as inevitable and mitigation necessitates expensive maintenance regimes; ~£40 billion/year is spent in the UK on repair and maintenance of existing, mainly concrete, structures. More recently, based on a better understanding and knowledge of microbiological systems, materials that have the ability to adapt and respond to their environment have been developed. This fundamental change has the potential to facilitate the creation of a wide range of 'smart' materials and intelligent structures, including both autogenous and autonomic self-healing materials and adaptable, self-sensing and self-repairing structures, which can transform our infrastructure by embedding resilience in the materials and components of these structures so that rather than being defined by individual events, they can evolve over their lifespan. We therefore advocate that next generation infrastructure will include next generation infrastructure materials based on smart biomimetic construction materials. This paper presents details of the national consortium that is leading international efforts in the development of those next generation infrastructure materials. It presents details of the work done to date, over the past three years, as part of the EPSRC funded project Materials for Life and the plans for work to be done over the next five years as part of a follow-on Programme grant: Resilient Materials for Life.

Key Words

Infrastructure materials, Advanced Materials, Biomimetic Materials, Resilience

Introduction

The UK recently committed to an investment of £100 billion in infrastructure by 2021[1] and currently spends half of its construction budget on the repair and maintenance of infrastructure, at ~£40 billion/year[2],[3]. Much of the UK infrastructure is concrete, here used to also include mortars, grout, and cement-modified soils. The design of these materials is based on using safety factors for individual adverse events and providing redundancy. As such, construction materials are designed to meet a prescribed specification; material degradation is viewed as inevitable and mitigation necessitates expensive inspection, maintenance, repair and eventually replacement regimes. There is much evidence describing problems experienced with existing concrete structures[4]. When transport-related structures cease being serviceable there are large societal costs associated with delays and disruptions. The cement and concrete industry have huge natural resource and energy demands and produce large amounts of CO_2[5]. Cement production alone is responsible for 5-8% of all anthropogenic CO_2 emissions[6]. It is widely recognised that more efficient and durable cementitious materials are needed if this industry is to make its contribution to climate change targets[7]. It is also acknowledged that concrete repairs are generally not very effective. In the EU, 20% of all concrete repair works fail in the first 5 years, 55% within the first 10 years and all within 25 years[8]. This leads to an inevitable continuous and extremely costly and disruptive cycles of upkeep of our civil infrastructure assets. The situation in the US is similar with $500 billion expected to be needed per year to restore its infrastructure[9]. Looking ahead we would expect the challenges associated with our infrastructure only to intensify, both in terms of construction as well as management. One challenge will be the significant increase in energy infrastructure: exploring deeper waters for off-shore wind farms, building deeper and more secure underground repositories for nuclear wastes and exploring deeper and more complex well-bore systems for new oil and gas explorations. In terms of our building infrastructure, our congested underground systems of tunnels, piles, shafts and services will only become more complex and will require extremely careful design and construction procedures to enable the installation of new infrastructure systems within and around the existing structures. Many of these structures are inaccessible or have prohibitive costs associated with their maintenance[10]. In addition, increasing the resilience of our infrastructure to cope with the impact of climate change is now a high priority for most governments[11],[12]. Adaptation against the anticipated severe storms and floods will require the construction of huge stretches of embankments, dykes, flood-walls and local storm surge barriers as is planned for major cities like New York[13].

Much of our vast concrete infrastructure assets are exposed to a myriad of damaging environmental actions and the severity of these actions is expected to intensify in the future. Damage in concrete structures manifests itself in different forms, such as macro-cracking, weakened areas of material, oxidation of reinforcement, loss of rebar cover, material dissolution, swelling and/or expansion as well as

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[13] NYC, 2013. A Stronger, more resilient New York, www.nyc.gov/html/sirr/html/ report/report.shtml

internal micro-cracking. This damage varies significantly depending on the concrete composition, construction procedures and exposure conditions and is very difficult to predict and quantify. As well as significantly reducing performance, these forms of damage can ultimately lead to the collapse of structures if critical internal damage is not detected early. Steel corrosion is the largest and most costly deterioration problem in reinforced concrete, with a UK annual budget of >£1 billion[14]. In the US, the total annual cost of corrosion on infrastructure is ~$23 billion, including ~$10 billion for bridges and highways[15]. Significant damage goes undetected and it is a huge challenge to design an optimum inspection and maintenance strategy.

Over the past two decades and based on a better understanding and knowledge of natural and biological systems, materials that have the ability to adapt and respond to their environment have been developed. This fundamental change has the potential to facilitate the creation of a wide range of 'smart' materials and intelligent structures and adaptable, self-sensing and self-repairing structures, which can transform our infrastructure by embedding resilience in the materials and components of these structures so that rather than being defined by individual events, they can evolve over their lifespan. Hence our long-term vision (2050) is of a sustainable and resilient infrastructure containing smart materials and structures that self-regulate, adapt and repair without external intervention. To achieve this a transformation in construction materials is required in the near future to create materials that will adapt to their environment, develop immunity to harmful actions, self-diagnose the on-set of deterioration and self-heal when damaged and the proposition of this paper is that this is best achieved through a biomimetic approach. This will engender a step-change in the value placed on infrastructure materials and provide a much higher level of confidence in the reliability of the performance of our infrastructure systems. The development of such advanced materials is clearly a major challenge and is something that the authors have worked on in collaboration over the past four years. Another challenge is that the construction industry remains the slowest sector to adopt or adapt to new technologies due to its historic conservative approach to product design and delivery[16], despite being the single largest global consumer of resources and raw materials, and accounting for 6% of GDP. Whilst recent breakthroughs and innovations in material science have resulted in significant advances in sectors as diverse as pharmaceuticals and electronics; construction materials have historically received relatively little attention and investment. Construction materials have suffered from being perceived fundamentally as a cheap and straightforward commodity, where the application of often expensive cutting-edge material technologies is simply not justified. Clearly, this view can no longer be sustained due to the huge volumes used and associated high carbon footprint as well as the extensive and expensive maintenance regimes that are needed to maintain our infrastructure assets.

Self-healing Infrastructure Materials

Our approach in tackling this huge challenge has been firstly to develop a suite of complementary technologies for self-healing physical damage at different scales, focusing on cracks, and showing how they could be combined in real applications[17],[18]. This was part of the EPSRC funded project Materials for Life (M4L) which ran between 2013 and 2016. Self-healing phenomena in cementitious systems are broadly divided into two categories: autogenous and autonomic. Autogenous self-healing refers to self-

[14] BRE, 2003. Residual life models for concrete repairs.
[15] NACE, 2002. Corrosion costs and preventative strategies in the US.
[16] Shaping the Future of Construction – A breakthrough in Mindset and Innovation, 2016. World Economic Forum Report.
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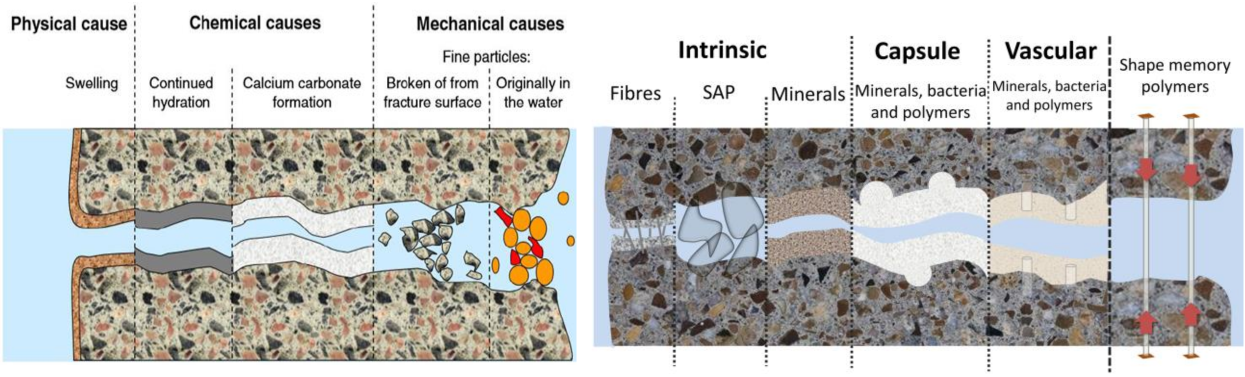
healing processes that are an intrinsic characteristic of the components of the matrix which are usually effective for small crack widths of ≤0.15mm. Autonomic self-healing refers to actions that use components that do not naturally exist in the cementitious composite, i.e. 'engineered' additions that are usually employed to deal with larger crack sizes. Examples of both systems are shown schematically in Fig. 1. Some autogenous and autonomic self-healing systems work in combination so that the autonomic system works to reduce the crack size to enable autogenic processes to complete the self-healing.



(a) (b)

Fig. 1. Self-healing phenomena in cementitious systems: (a) autogenous self-healing[19] and (b) autonomic self-healing[20].

The autonomic self-healing systems we have developed to date include the following:

Microcapsules (Fig. 2): Micron size capsules that contain a healing agent. For cementitious systems the challenge is to use suitable and compatible materials for both, that will enable survivability during the mixing, effective bonding between the shell and the cementitious matrix, longevity within the matrix, appropriate rupture when intersected by a crack and adequate release of the healing agent. The healing agent in turn needs to have a long shelf-life, to effectively flow out of the fractured capsule and to be capable of forming effective sealing and healing products. The most promising developments to date have included microcapsules with polymeric, gelatin/gum Arabic or polyurea, shells and a sodium silicate cargo[21]. These have been developed in collaboration with industrial partners and have been shown to be capable of withstanding high shear mixing. Work has been carried out on size and dosage of microcapsules for different cementitious composites.

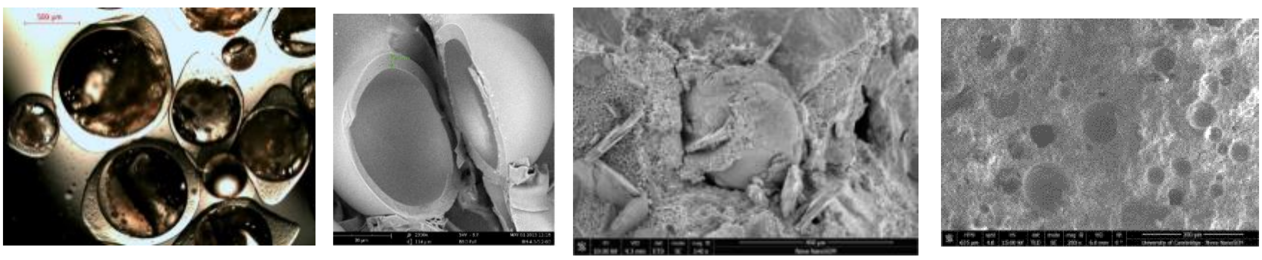
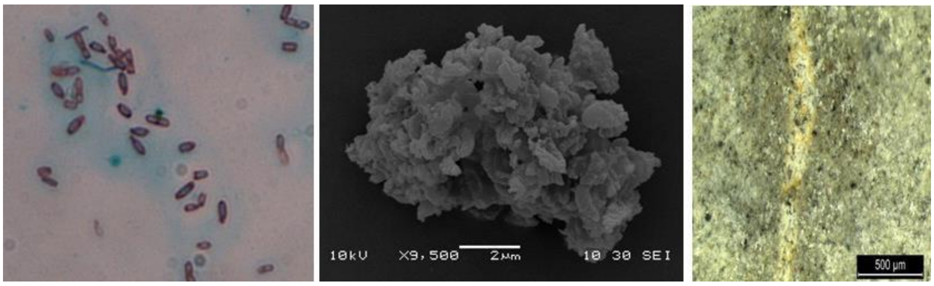


Fig. 2. Self-healing microcapsules developed and tested within cementitious matrices.

[19] De Rooij MR et al, 2013. Self-healing phenomena in cement-based materials, Springer.
[20] Ribeiro de Souza L, 2017. Design and synthesis of microcapsules using microfluidics for autonomic self-healing in cementitious systems. PhD Thesis, University of Cambridge, UK
[21] Kanellopoulos A, Giannaros P, Palmer, D, Kerr A & Al-Tabbaa A. 2017. Polymeric microcapsules with switchable mechanical properties for self-healing concrete: synthesis, characterisation and proof of concept. Journal of Smart Materials & Structures, 26: 045025 (15pp).

Calcium carbonate-precipitating bacteria (Fig. 3): The bacteria-based approach works by encapsulating bacteria spores and a calcium precursor within the material. On appearance of a crack the bacteria germinate and by metabolic actions precipitate calcium carbonate within the crack. Research has led to the creation of a bespoke combination of alkaliphilic *Bacillus* bacteria, nutrients and precursors that rapidly precipitate calcium carbonate and return the permeability of concrete to that prior to cracking. The first ever critical analysis of the kinetics of bacterial calcium carbonate formation demonstrated that it was possible to tailor the nutrients to maximise mineralizing capacity using a selection of microbiological aids that were compatible with concrete hydration[22]. The microencapsulation of bacteria and nutrients was proven for the first time.



(a) (b) (c)

Fig. 3. (a) Spores of *Bacillus pseudofirmus* (b) calcium carbonate precipitated by *B. pseudofirmus* and (c) self-healing of a crack by the action of *B. pseudofirmus*.

Shape memory polymers (SMP, Fig. 4(a-c)): The SMP system employs pre-drawn PET tendons to close cracks in concrete structural elements. These tendons are cast into a concrete structural element and electrically activated after cracking occurs. They are anchored at discrete locations so that when they are activated, a released restrained shrinkage potential applies an internal compressive force to the structural element. This compressive force tends to close any cracks that have formed within the cementitious material. The ability of the tendons to maintain a significant post-activation crack closure force is important to the viability of the self-healing system. A series of tests explored the long-term relaxation of the restrained shrinkage stress within SMP tendons and research was undertaken to scale up this technology and develop higher performance tendons, producing a new tendon assembly that comprised multiple SMP filaments[23], an outer spiral wire for electrical activation and a plastic sheath for protection.

Vascular networks (Fig. 4(d)): Vascular networks are a set of connected capillary tubes that resemble the human blood vein system. A series of combined numerical-experimental studies[24] have been undertaken to investigate the capillary flow properties of healing agents in planar concrete cracks. These studies have explored the transport behaviour of a range of natural and autonomic agents in manufactured (smooth) and natural (rough) cracks of varying apertures. These studies have established parameters that quantify viscous resistance, capillary tension, contact angle, meniscus resistance, stick-slip and wall-resistance characteristics. In addition, the authors have proposed a model based on a modified form of the Lucas-Washburn equation for capillary flow and have shown that this model is able to accurately predict the

[22] Sharma, T., Alazhari, M., Heath, A., Paine, K., Cooper, R. 2017 Alkaliphilic *Bacillus* species show potential application in concrete crack repair by virtue of rapid spore production and germination then extracellular calcite formation. Journal of Applied Microbiology, 122: 1233-1244.

[23] Teall O, Pilegis M, Sweeney J, Gough T, Thompson G, Jefferson A, Lark R, Gardner D. 2017. Development of High Shrinkage Polyethylene Terephthalate (PET) shape memory polymer tendons for concrete crack closure, Smart Materials and Structures, 26(4).

[24] Gardner D, Herbert D, Jayaprakash M, Jefferson A, Paul A. (2017). Capillary flow characteristics of an autogenic and autonomic healing agent for self-healing concrete. Journal of Materials in Civil Engineering (accepted)

flow properties of a range of healing agents in planar cracks. An innovative means of creating a vascular network in concrete elements using polyurethane tubing has been developed and its ability to deliver agents proven.[25] This procedure is considered viable for small to moderate sized structural elements and for the surface zones of larger structural elements. The major advantage of the system is that it can, in principle, deliver unlimited quantities of healing agent to a damaged zone.

(a) (b) (c) (d)

Fig. 4. (a-c) Shape memory polymers and tendon assembly developed and tested within cementitious matrices and Fig. 4 (d) Vascular networks developed and tested within cementitious matrices

Field Deployment and Applications to Date

In the UK two full-scale projects have recently been undertaken, one a demonstration project and the other a commercial application – both conducted by the M4L project team. The demonstration project was undertaken on the Welsh Government A465 Heads of the Valleys Upgrade project for which Costain are the main contractor. It involved the construction of a series of full-scale concrete retaining walls[26] each of which was 1.8 m high and 1 m wide, as illustrated in Figure 5. These reinforced concrete panels included a control panel and four self-healing panels, in which different combinations of the M4L self-healing systems were embedded. The panels were constructed in September 2015 and then subjected to damage and allowed to subsequently heal. This deployment showed conclusively that the technologies can be scaled-up and deployed together in real structural elements (Fig. 5a-b). The response of the panels in both pre and post-healed conditions were monitored with a range of in-situ instrumentation and visualisation techniques. Monitoring is still on-going and although the healing results obtained to-date are mixed, all of the systems offer promise for the future. The commercial application formed part of the new James Dyson Building extension to the Department of Engineering at the University of Cambridge in June 2015. A total of 100 self-healing concrete blocks (440x220x100mm) were manufactured in-house and used in place of commercial blocks to form the walls of the plantroom on the roof of the building (Fig. 5b). This was agreed with the design team, and strength performance was provided. The only requirement was to reduce their thickness compared to the commercial blocks, since they were not tested for fire resistance and hence a suitable coating was applied to them to satisfy that requirement. Enhancement of the commercialisation of the developed microcapsule systems is also underway in concrete repair grouts and oil-well cementing applications, both in collaboration with different industrial partners. The team is also currently in discussions with HS2, the A14 project and Tideway regarding additional field trials.

[25] Davies RE et al. 2015. A novel 2D vascular network in cementitious materials. Fib symposium, Copenhagen, Denmark.

[26] Teall O, Davies R, Pilegis M, Kanellopoulos A, Sharma T, Paine K, Jefferson A, Lark R, Gardner D, Al-Tabbaa A. 2016. Self-healing concrete full-scale site trials. 11th FIB Int. PhD Symp. Civil Eng, Tokyo.

(a) (b)

Fig. 5. Demonstration and commercial application of self-healing concrete in 2015: (a) Field trial panels on the A465 site and (b) concrete blocks in the new James Dyson Building in Cambridge.

Commercial Parameters

Potential benefits: To date, there has been high level support for the potential benefits that can be expected from the development of biomimetic self-healing infrastructure materials. There has been significant interest and engagement from client organisations (Highways England, HS2) and companies across the whole supply chain: contractors (Costain, Laing O'Rourke), consultants (Arup, Atkins), material suppliers (Tarmac, Cemex, Travis Perkins) and chemical companies (Fosroc, Lambson, Graphitene, Micropore Technologies). They have identified practical applications of the developed technologies which will be focused on moving forward. There was a positive outcome from a market research exercise conducted for us by Lychgate, who surveyed and interviewed over 40 major construction organisations, including clients, contractors, consultants and producers[27]. This survey clearly showed that construction professionals have continuing problems with current cementitious materials e.g. cracking in new concrete structures within the last two years was reported by > 90% of those surveyed. The survey also showed the major appetite for self-healing materials amongst construction professionals, who recognised the huge benefits that these materials could bring in a variety of situations. The applications identified included, bridges and highways, marine and water retaining structures, aggressive environments where chemicals are present, tunnels (at joints, in sprayed concrete and precast elements), nuclear installations, dams, highway pavements, concrete piles and airport runways. The benefits include self-healing of cracks, reduced use and costs of over-design to provide resilience, the need for fewer additives and reduced concrete cover and reinforcement. Recent success and the significant advances that have been made in the Netherlands on the development of biological healing for concrete (bioconcrete) which is currently being commercialised[28] provides confidence in the proposed technologies. The development and commercial application of self-healing asphalt also in the Netherlands brought home what can be similarly realised with concrete. The first self-healing asphalt road section in the Netherlands was constructed in 2010 on a section of a motorway[29] and this technology is predicted to save the Dutch €90m/year if used everywhere, and has now been implemented on four other motorways. Another relevant success is the

[27] Lychgate, 2016. Self-healing concrete – potential applications and benefits, Lychgate Projects Ltd.
[28] Wiktor V & Jonkers H 2016. Bacteria-based concrete: From concept to market. Smart Mat. & Struct, 25 (8).
[29] Liu Q, Garcia A, Schlangen E, Ven M Van De 2011. Induction healing of asphalt mastic and porous asphalt concrete. Constr Build Mater, 25:3746–52.

development of a self-healing oil well cementing system by Schlumberger[30]. Cementing is extremely important in downhole zonal isolation and sealing where the downhole environment is particularly hostile and inaccessible. Poor cementing has been linked to the Macondo oil rig disaster in the Gulf of Mexico[31]. The successful commercialisation of self-healing materials in other sectors is also encouraging self-healing car paint[32] and self-healing polymer composites for the aerospace industry through the US spinout companies from University of Illinois: Autonomic Materials[33]. The government Technology and Innovation Futures 2017 report identified the use of self-healing materials as potential vehicles for self-repair in future smarter roads[34] and the 2016 World Economic Forum report: Shaping the Future of Construction[25] has identified self-healing materials as a new radical innovation in construction. The EU estimates that 70% of product innovation across all industries is derived from new and improved materials. With around one third of construction costs attributed to building materials, the scope for applying advanced building materials is considerable[35].

Cost of introduction: Various cost and economic feasibility analyses and studies have been conducted. In the Lychgate market research study[27], a 20% increase in initial cost was considered viable based on advice from concrete producers, although it was clear from the industry partners consulted that they were aiming for a much lower premium. A whole-life costing exercise for a bridge deck currently under construction was carried out[36]. Adaptations were made to deterioration curves in the Structures Asset Management Planning Toolkit (SAMPT) to allow self-healing concrete deck slabs to be modelled with varying numbers of self-healing cycles. The adapted model was used to carry out a life cycle cost (LCC) assessment, using a bridge constructed as part of the A465 Heads of the Valleys road improvement project as a case study. The LCC of the structure was modelled, comparing the costs associated with a conventional reinforced concrete deck slab against a self- healing concrete deck slab capable of one, two, three and indefinite healing cycles. The results of this assessment demonstrated that a concrete deck slab capable of a single healing cycle would not reduce the LCC of the structure. However, with multiple healing cycles the LCC is reduced significantly, saving up to ~12% of the structure's construction and repair costs. Given the relatively low material cost of the concrete deck slab compared to the potential savings over the 120-year study period, this finding means an increase in material cost of up to 20 times could be justified for the use of a self-healing concrete capable of multiple healing cycles. A sensitivity analysis was carried out by altering key variables within the model and observing the change in outputs. This analysis found that the model is very sensitive to the exposure class used; a self-healing concrete deck slab is most viable for structures subject to severe exposure conditions, with little if any cost benefit seen in mild exposure conditions. The calculated cost savings are also sensitive to changes in the study period and discount rate, although across the range of values investigated for both of these variables, the overall conclusions of the study remain the same. This life cycle cost assessment has given an indication that a self-healing concrete, capable of multiple healing cycles, would yield a positive cost benefit when used for the concrete deck of contemporary bridges in severe exposure conditions over the design life of the structure. The very recently commercialised self-healing coating by Autonomic Materials[33] is reported to be cost neutral.

[30] FUTUR - Self-healing cement, Schlumberger, 2011, www.slb.com/services/drilling/cementing/self_healing_cement.aspx.
[31] CBC News, www.cbc.ca/news/world/bp-oil-disaster-largely-blamed-on-cement-failure-1.1057694
[32] www.xpel.com/mercedes-benz-slr-mclaren-gloss-to-matte-black-with-self-healing-film-houston-texas/
[33] www.autonomicmaterials.com/
[34] Technology and Innovation Futures 2017, Government Office for Science.
[35] European Commission 2014. Smart Living: Advanced building materials, Brussels.
[36] Teall O. 2017 Crack closure and enhanced autogenous healing of structural concrete using shape memory polymers. PhD thesis, Cardiff University.

Main challenges and barriers: The main challenges and barriers which need to be addressed to enable the maximum uptake of the technology include the following: (i) further extensive validation data is needed to provide industry with the confidence it requires in the systems that have been developed to-date and, in particular, the long-term performance of the systems and their response to cyclic and time-dependent actions need to be established, (ii) the material systems need to be certified to prove compliance with national and international standards, (iii) design procedures and analysis methods are required before the proposed systems can be safely applied, (iv) development and exploitation costs need to be appropriate to ensure commercial viability and (v) conservativeness of the construction industry – hence ideally entering the construction market through say the repair market would provide evidence of performance. It is also important to recognise that the implementation of smart biomimetic construction materials may create a paradigm change in the way we have to approach design and performance of our infrastructure. It has been suggested that this requires consideration of the governance structure of the national and municipal authorities which regulate the different infrastructure layers and the need for additional project management effort to implement such novel technologies. However, research on the implementation of innovative and sustainable construction materials has shown that that the management of the innovation process requires the creation and navigation between four discreet phases of design activity[37]. In the first phase there needs to be an open attitude to innovation and accommodation of the uncertainty afforded by new materials. In phase 2 there is a need for a timely transition to an analytical assessment of the materials in which information should be sought and validated, and risks identified. The third phase is concerned with enacting formal risk procedures and contractual arrangements. Finally, phase 4, should be reflective and recognise project learning and achievements. In general, the introduction of this technology should not imply major changes to existing infrastructure, and will fit with existing infrastructure and methods of construction. Furthermore, the introduction of self-healing materials will not make previous infrastructure redundant.

The Next Stage

The team is now focusing on the planned activities for the next five years as part of a £5M EPSRC Programme grant to take forward the developments to date focussing on specific commercial applications and addressing the more complex and realistic damage scenarios and conditions. The research elements will include: (i) addressing the challenges of dealing with the diverse damage conditions that can be expected including cyclic damage, time-related damage and chemical damage, (ii) focussing on specific applications for rapid commercialisation, (iii) in collaboration with industry, tackling the various issues with scaling up of the developed technologies, (iv) initiating ground-breaking research on embedding capabilities for self-sensing, self-diagnosing, self-immunisation and self-reporting to develop truly biomimetic responses in our infrastructure materials and structures. These research objectives will be achieved through an ambitious programme of strongly inter-woven research work encompassing the four complementary technology areas of self-diagnosis, self-healing, modelling and tailoring and scaling up. Five main application areas (cast in-situ, precast sections, repair, overlays and geotechnical applications) will form the cross-cutting strands that will integrate the technologies, direct the work towards practical and relevant scenarios and directly engage the RM4L industry partners in the research. The programme grant is divided into four research themes. Research Theme 1 on self-healing of cracks at multiple scales will expand the work performed to date on the developed self-healing

[37] Grist, E. 2014. The implementation of innovative and sustainable construction materials. EngD thesis, University of Bath, 354pp

systems, namely microcapsules, bacteria, shape memory polymers and vascular networks. It will target the identified set of applications to ensure that the proposed developments are focussed on the requirements of industry and refine and optimise the developed self-healing systems for those applications. Research Theme 2 on self-healing of time-dependent and cyclic loading damage will include research on self-healing systems that can heal multiple occurrences of damage. This will explore methods for healing damage caused by, for example, extrinsic cyclic actions on bridges and earthquake loading on building structures. This will present a host of research challenges related to the speed of action of healing agents, continuous availability of healing material and multiple activation potential of self-healing systems. This research theme also aims to find novel solutions for counteracting damage from intrinsic time-dependent phenomena such as creep, shrinkage and early age thermal effects. Research Theme 3 on self-diagnosing and self-immunisation against physical damage will develop intelligent and resilient materials that can self-sense damage, self-diagnose the significance of the damage, and self-control a response. These materials are envisaged to be able to detect on-coming physical damage and respond appropriately before any damage and loss of performance actually occurs. Research Theme 4 will address self-diagnosing and self-healing of chemically-included damage which afflicts cement-based materials in a multitude of applications and there are a host of different external and internal chemical environments that cause such damage. The single most costly problem induced by a chemically aggressive environment is corrosion in reinforcing and prestressing steel components. Research activities will address these problems and conduct research to find techniques for diagnosing, creating immunity to, and healing the most common forms of chemically induced damage in cement-based materials.

Conclusions

This paper advocates that the next generation infrastructure will include next generation infrastructure materials based on smart biomimetic construction materials. This is the mission that the authors and their teams and wider academic and industry partners have set themselves over the past 4 years and next five years. A number of complementary self-healing components for cementitious systems have been successfully developed. This includes (i) microcapsules with switchable mechanical properties and with mineral healing cargo, (ii) bespoke combinations and microencapsulation of alkaliphilic bacteria, nutrients and precursors for rapid precipitation of healing products, (iii) innovatively created vascular network using polyurethane tubing, (iv) remotely activated shape memory polymer multi-strand sheathed tendons and (v) a complementary computational modelling framework. Two field applications have been undertaken to date to validate the scaling up of the developed systems and their success at delivering self-healing at full-scale. There is significant level of interest from industry in taking these developments forward. Associated market research identified continued deterioration problems and the benefits of self-healing cementitious systems. Cost and economic viability studies have provided assurances of whole life cost-effectiveness for self-healing cementitious systems. The work has also identified a number of challenges and barriers. The next five years will see this research work expanded to a completely different level of complexity, breath, and practical applications.

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