THE FUTURE OF INFRASTRUCTURE

RESILIENT MATERIALS FOR LIFE

RESILIENT MATERIALS 4 LIFE

The cost of concrete

£40
billion spent each year in the UK on maintaining mostly concrete infrastructure[1]

↓

=50%
of its national infrastructure budget[2]

20%
of repairs fail after 5 years[3]

↓

55%
after 10 years[4]

Concrete and cementitious systems

Concrete is made by mixing fine and coarse aggregates with a liquid cement paste that hardens over time. Concrete is just one of the materials RM4L is concerned with: the programme covers all kinds of cementitious systems, which include materials such as mortar, grout and cemented soils as well as concrete.

1 ONS (2016) Construction output in Great Britain: May 2016, www.ons.gov.uk

2 ONS (2016) Construction output in Great Britain: May 2016, www.ons.gov.uk

3 Tilly, G and Jacobs, J (2007) *Concrete repairs: Performance in service and current practice*, BRE Press

4 Tilly, G and Jacobs, J (2007) *Concrete repairs: Performance in service and current practice*, BRE Press

5 Habert, G et al (2020) 'Environmental impacts and decarbonization strategies in the cement and concrete industries', *Nature Reviews: Earth and Environment*

6 'Making Concrete Change: Innovation in Low-carbon Cement and Concrete', Chatham House Report, 2018

7 'Making Concrete Change: Innovation in Low-carbon Cement and Concrete', Chatham House Report, 2018

Environmental impact

10 billion
cubic metres of concrete produced each year[5]

4 billion
tonnes of cement (the main component of concrete) are produced globally each year[6]

8%
of global CO_2 emissions result from cement production[7]

RM4L

4
universities

50+
researchers

20+
international industry partners

RM4L: Introduction

Tony Jefferson, Professor of Civil Engineering, RM4L Principal Investigator

The idea for the Resilient Materials for Life (RM4L) programme grant was conceived by a team of investigators from Cardiff, Cambridge, Bath and Bradford universities, and developed from the forerunner Materials for Life (M4L) project. The latter was successfully completed in 2016 and culminated with a site trial in which multiple new self-healing materials were used to form a series of structures on a live construction site. M4L proved the viability of self-healing construction materials but the team recognised that a more sustained and wider-ranging research effort was required for the potential of biomimetic construction materials to be fully realised.

An expanded multidisciplinary team of leading academics was assembled with expertise in micro-biology, chemistry, physics, materials science, mathematical modelling and civil engineering. This diverse team developed a programme of research to explore materials that could self-diagnose and self-immunise as well as self-heal. The programme also addressed the critically important issue of the long-term durability of these materials. An EPSRC programme grant was identified as the ideal mechanism for funding the required research. The team developed a successful bid and RM4L began in April 2017.

RM4L's vision was to achieve 'a transformation in construction materials using the biomimetic approach first adopted in M4L 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'. The vision was bold and achieving it over the past five and half years has involved overcoming many challenges, including the effects of the COVID-19 pandemic.

The achievements of RM4L are many and various. They include the development of new biomimetic systems for healing, diagnosing and immunising against damage in a range of construction materials. New 3D software for simulating self-healing materials has been developed and used to accelerate the development of new systems. Life-cycle assessments have been undertaken to show the long-term viability and benefits of the new material systems. Fifteen RM4L biomimetic technologies are considered well-advanced in their

CNC machining, a technique used to manufacture moulds for injection moulding.
Credit: University of Bradford

Trialling a range of cement-based materials in the Dyson Building, Department of Engineering, University of Cambridge.
Credit: University of Cambridge

"RM4L has changed the landscape for biomimetic construction materials in the UK and beyond."

development and, of these, one is being commissioned, seven are undergoing large-scale long-term tests and the remainder are being validated with medium-scale pilot experiments.

Fundamental research has shown how to detect damage before it happens and automatically activate a system that prevents cracks from developing. Ground-breaking work has been undertaken on using carbon-based nanomaterial composites for self-sensing and novel low carbon encapsulated additives for effective immunisation against corrosion damage in reinforced concrete structural elements. A library of characterised bacteria, suitable for a range of challenging environments and applications, has been produced and tested exhaustively in cementitious environments. This work has transformed the potential of microbial-based healing systems.

RM4L has developed the careers of more than 20 post doctoral researchers who have worked on the project. They have gained considerable multidisciplinary research expertise in biomimetic materials. A number have become full-time academics, some have progressed to other research projects, whilst others have joined our industrial partners as full time employees. In addition, more than 30 PhD students have completed their theses on RM4L-related work. One of the most positive legacies from RM4L is embodied in the diverse community of young researchers who have worked together in a fantastically collaborative fashion on the project.

RM4L had an industrial advisory board comprising representatives from leading contractors, design companies, material suppliers and governmental bodies. The board provided invaluable advice to the investigators ensuring that the research remained relevant to industry. Costain and National Highways provided funding for researchers and opportunities to test technologies at large scale. An external scientific board comprising leading international researchers helped to steer the research providing immense encouragement and important guidance on the technical research of the project.

RM4L research has been disseminated in more than 150 technical papers and has been presented at more than 35 conferences. A successful international conference was organised by the project partners. The work of RM4L has been publicised in a number of national and local television and radio broadcasts, and in YouTube videos. The team has presented at science exhibitions and industry events.

RM4L research is continuing in several new and ongoing projects; in particular, by Cambridge through the Digital Roads of the Future initiative in partnership with National Highways and Costain. Our industrial partners are also funding large scale trials over the next few years and the whole team is preparing a number of ambitious future schemes.

RM4L has changed the landscape for biomimetic construction materials in the UK and beyond. It has transformed the field and the partners believe its legacy will be 'a transformation in construction materials'. Read more about the research, the team and achievements in the following pages.

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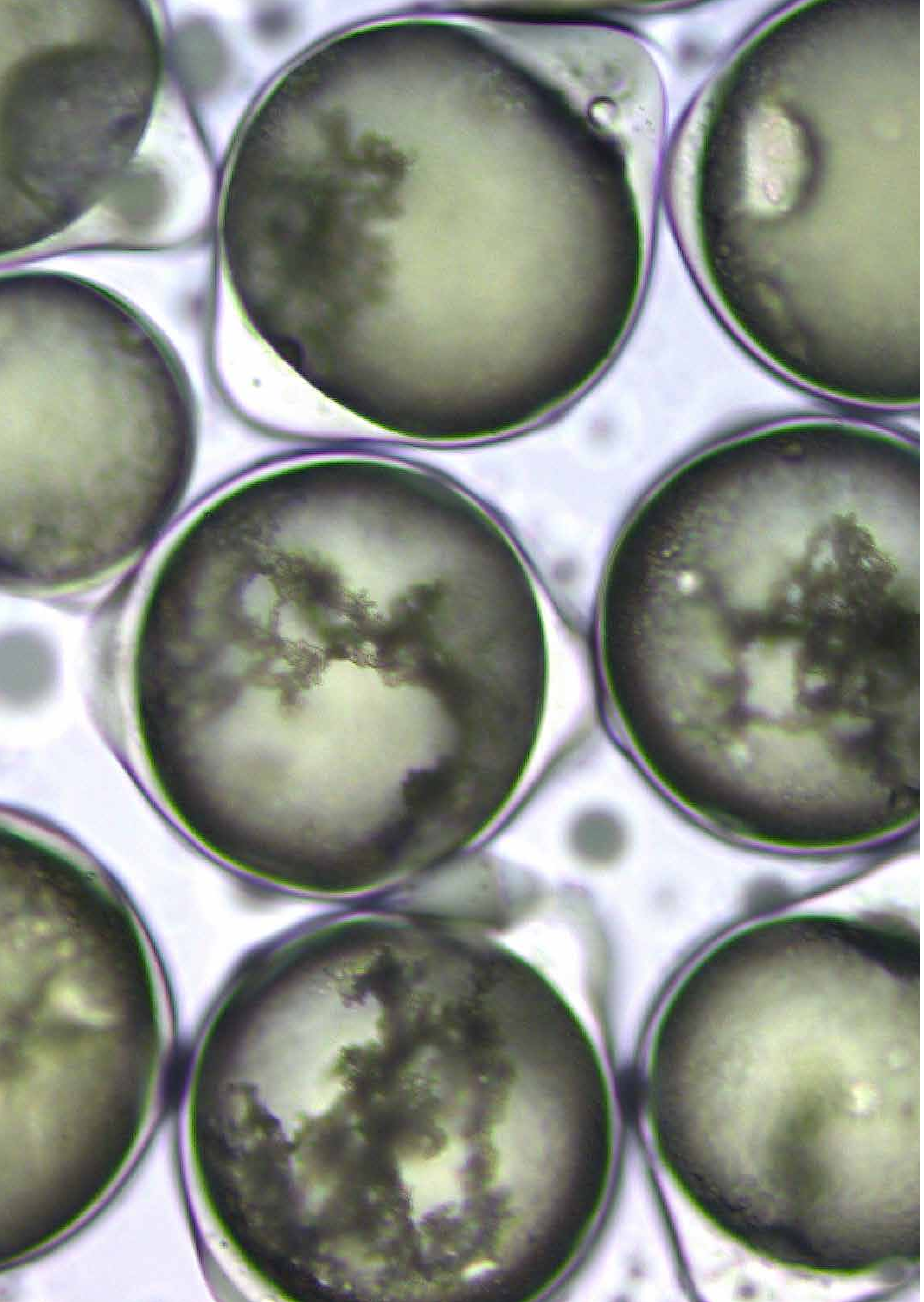


The future of concrete

Concrete is an amazing material which has been improving the quality of human lives for thousands of years. It has been found in structures dating as far back as 6500 BCE in Syria and Jordan, it helped build the Pyramids of Giza and the Great Wall of China and it was the Romans' building material of choice.

Concrete today

We use it today for the same reasons our forebears did: it is strong, relatively inexpensive, and can be cast into whatever shape an engineer requires. However, concrete is not perfect: it may deteriorate over time and, in particular, has a propensity to crack. Cracks are a problem because they let in water and harmful substances causing further damage and for reinforced and pre-stressed concrete this can lead to corrosion of the steel. Although the quality and durability of concrete has improved significantly over the last 20 years, today's formulation is still prone to cracking. Many structures built using concrete, particularly before the end of the twentieth century, are deteriorating in front of our eyes and are in need of constant monitoring and endless repair.

Developed countries, with large numbers of concrete structures dating back decades are spending billions of dollars each year just to keep them functioning.

Workers at risk

Large structures that need constant monitoring and repair put construction workers at risk. When working on bridges, for example, in confined spaces or alongside traffic, they regularly find themselves in dangerous situations.

Impact on the environment

Because it has been so successful, concrete is everywhere. For every person on the planet, nearly two tonnes of concrete are manufactured and used by the construction industry each year. Producing cement, the main active component of all that concrete, is responsible for around 8% of global CO_2 emissions.

RIGHT
Making bacteria-based self-healing mortar. Credit: University of Bath

LEFT
Linseed oil microcapsules. Credit: University of Cambridge

If the world is to halve its carbon emissions by 2030 and limit the rise in global temperatures, the concrete industry needs to find a way of becoming net zero. At the same time, however, we also need to recognise the vital role concrete has to play in delivering social and economic improvements to developing economies. If nothing changes over the next 30 years, we are on course to producing more than five billion tonnes of cement a year.

There is, then, an urgent need to find ways to use less concrete in construction and to make sure that what is built, lasts as long as possible.

Taking inspiration from nature

When a living organism is damaged – assuming that damage is not too overwhelming – it is able to heal itself. For some time, scientists have been developing new materials that can behave in a similar way: they can sense and diagnose their own 'injuries' and repair them without human intervention. This approach has been proven, with self-healing polymers and asphalt already on the market.

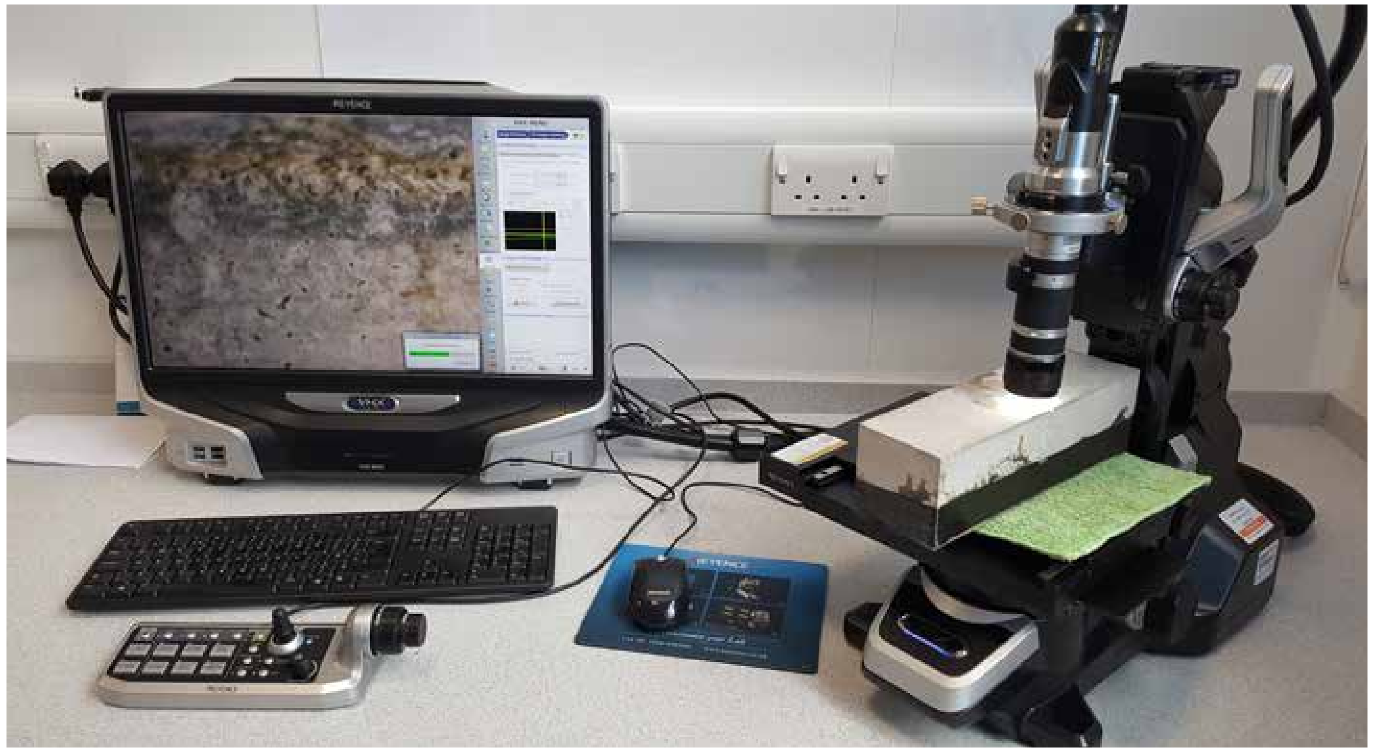
Concrete that can repair itself is a much bigger prize. It would dramatically cut the costs of maintaining buildings and infrastructure and reduce construction workers' exposure to risks. Extending the life of buildings instead of having to demolish and rebuild them when they eventually fail, would contribute to a reduction in CO_2 emissions. A stronger, longer lasting, self-sensing, self-healing concrete could also be used in smaller quantities: structural elements could be thinner and need less reinforcement – and hence less cement.

However, concrete is also a more complex material than either of the self-healing pioneers, polymers and asphalt. It suffers from different types of damage at different scales, requiring different solutions. RM4L researchers have been working on a range of breakthrough technologies to tackle these different challenges. They include embedding tiny capsules containing healing agent or putting dormant bacteria inside granules where these bacteria activate on contact with water and oxygen to produce a limestone repair.

"This project is a true testament to how like-minded clients – such as HS2, National Highways, Tideway – have come around the table with the research team and unlocked opportunities to explore novel and smart materials in the national interest.

The programme has provided real evidence that by working together we are able to move things forward, with some technologies now very close to market and some of the most promising hot on their heels."

Tim Embley
Director of Innovation, Costain and Chair of RM4L Industrial Advisory Board



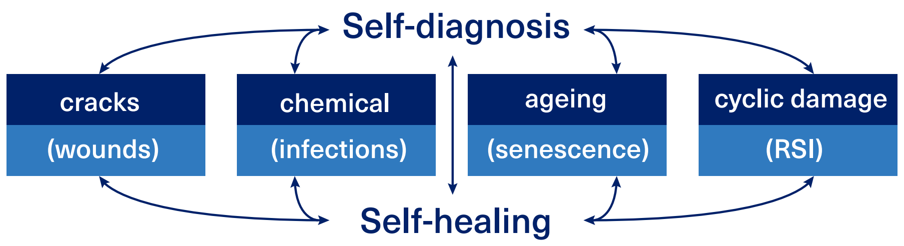
Visual inspection of a self-healing concrete specimen. Credit: University of Bath

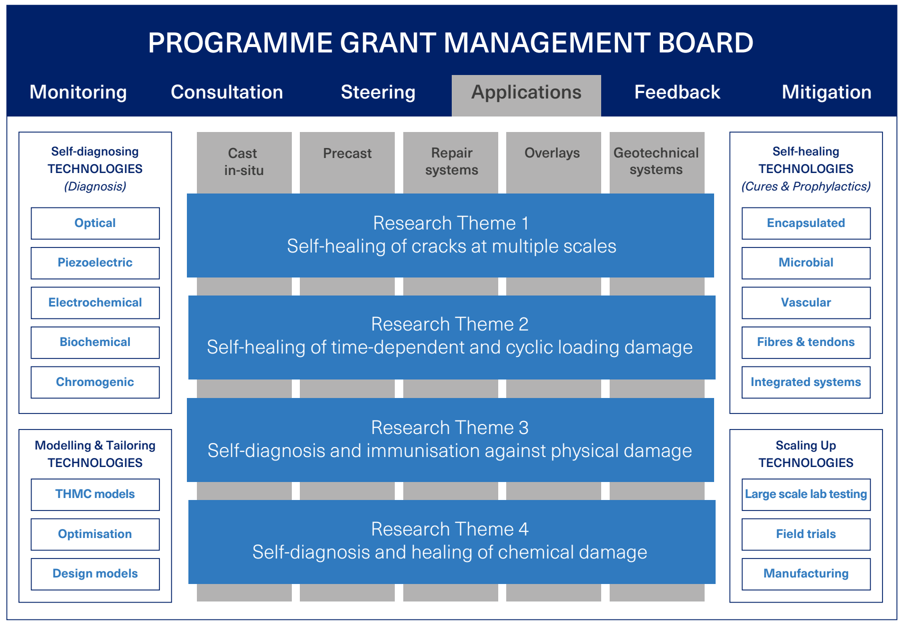
The RM4L research programme

The need to develop resilient structures, whilst being prudent with our natural resources has never been more pressing. Since planning the RM4L programme grant in 2016, the landscape surrounding climate change has altered significantly. As a research consortium, we had an ambition that by 2050 we can create a sustainable and resilient built environment and infrastructure comprising materials and structures that continually monitor, regulate, adapt and repair themselves without the need for external intervention.

RM4L was a key enabler of this ambition, with its own vision of achieving (by 2022) a transformation in construction by creating biomimetic materials that adapt to their environment, develop immunity, self-diagnose damage and self-heal when required, much like all natural biological systems.

This RM4L vision was crafted by the programme grant team, led by Cardiff University with the Universities of Bath, Bradford and Cambridge as partners. Alongside the wider scientific and industrial advisory boards and industrial project partners, a multidisciplinary RM4L team was formed with expertise in construction materials, structures, geotechnics, computer modelling, materials science, polymer engineering, nanomaterials, electrochemistry, biomaterials and microbiology, comprising engineers, material scientists, microbiologists and chemists.





The confidence to expound the vision was derived from the successes of the M4L project, as well as from a deep understanding of the challenges of introducing biomimetic materials into the construction industry. The innovative research into smart materials in RM4L will engender a step-change in the value placed on infrastructure materials and provide a much higher level of confidence and reliability in the performance of our infrastructure systems.

The ambitious programme of inter-related work was divided into four research themes. These brought together the four complementary technology areas to address a diverse range of applications found in the construction industry: self-diagnosing, self-healing, modelling and tailoring, and scaling up. Work packages interwoven across the research themes have ensured impactful collaborations between PhD students, researchers and staff in all four universities.

The four research themes

1. Self-healing of cracks at multiple scales in which the primary aim has been to develop and validate a suite of technologies for healing cracks in cementitious composites, suitable for a wide range of applications. The research has explored some fundamentally new ideas for achieving self-healing and bringing to fruition the range of multi-scale technologies considered in M4L.

2. Self-healing of time-dependent and cyclic loading damage in which the primary aim has been to develop self-diagnosing and self-healing systems to prevent and/or mitigate damage from both long and short-term intrinsic and extrinsic time-dependent actions.

3. Self-diagnosis and immunisation against physical damage in which the primary aim has been to develop truly self-diagnosing, self-healing materials that require no human interaction, and highly resilient concrete that self-strengthens prior to damage.

4. Self-diagnosis and healing against chemical damage, the primary aim of which has been to develop new systems that will be able to self-diagnose and act appropriately against chemical damage triggers in cementitious systems, both to self-immunise and prevent damage, or to self-heal damage once it has occurred.

The four research themes have been led by four lead investigators (RM4L Directors), who met monthly to address technical progress and non-technical matters. The programme grant has been steered by two advisory boards, the External Scientific Board and the Industrial Advisory Board, both of which met biannually. They, together with our industrial partners, have provided invaluable support and guidance to the RM4L Directors and ensured the practical relevance of the technologies we have developed over the last five years.

The entire project team, including all academics, researchers, industrial partners and scientific advisers have met at four annual forums, with researcher meetings taking place between these forums.

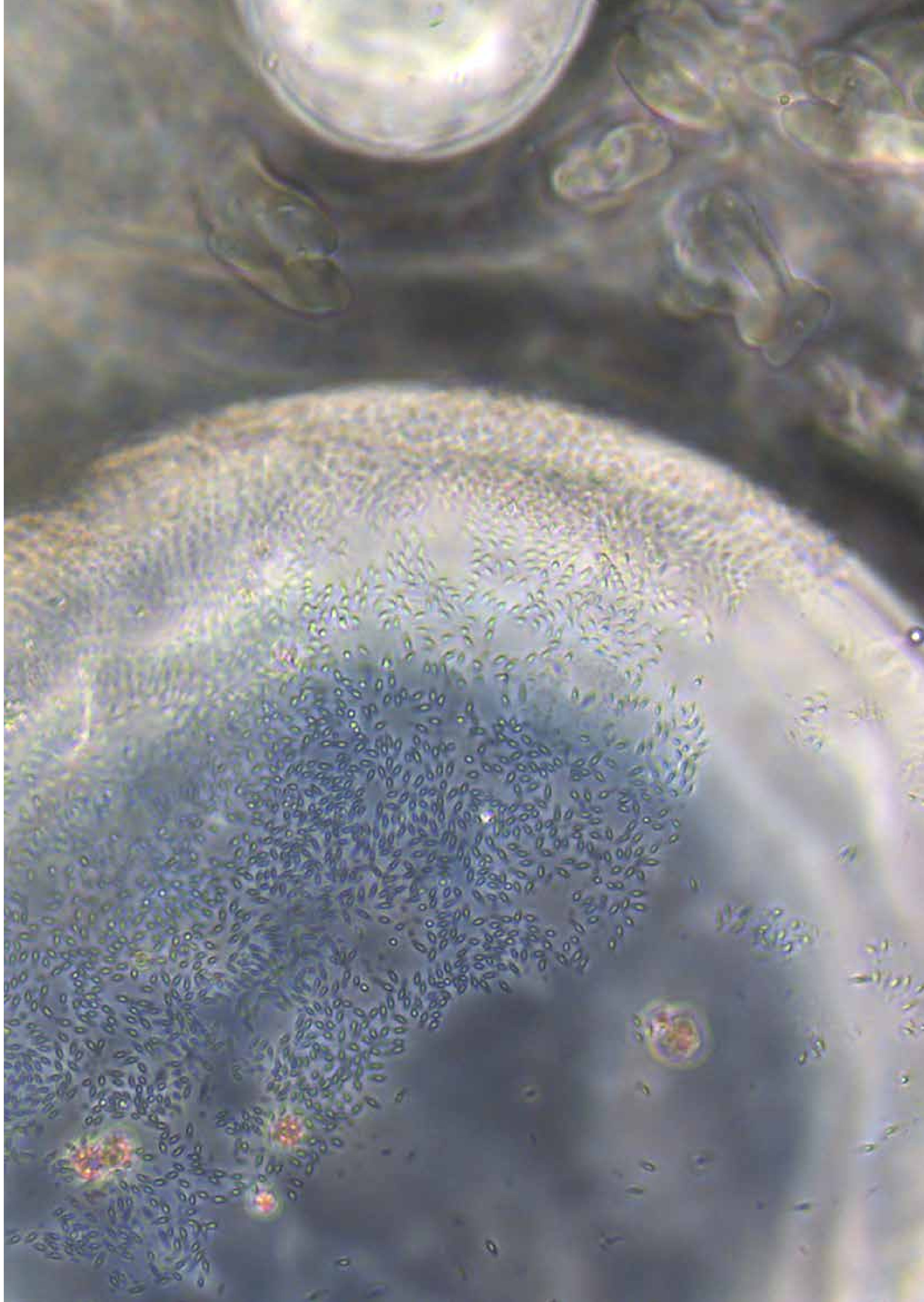
These gatherings have been fruitful events that appraised the research, generated new ideas and brought the cross-university research team closer together. The RM4L Directors ensured that the interlinked research strands remained focused on the project objectives and industrially relevant. We also encouraged the researchers to regularly interact and collaborate via documented monthly meetings, and visits to each other's institutions.

A focus of the work undertaken in the programme grant in its final year has been on scaling-up technologies, long-term tests and life cycle analyses of the developed systems. By virtue of the close intra-project collaboration, we have successfully combined technologies that have been proven to work effectively at smaller scales, in larger scale trials. However, there remains fundamental work to be done on other technologies with a view to widening the range of applicability and improving the efficacy of biomimetic systems for construction materials for particular applications.

In the following sections we take a closer look at some of the key areas of research and the technologies emerging from them.

ABOVE
Fibre extrusion, the first step in the manufacture of shape memory polymer. Credit: University of Bradford

RIGHT
A microcapsule containing spores. Credit: University of Bath



Mini-vascular networks and shape memory polymers

Over its lifetime concrete – and other similar materials – is likely to need regular repairs. Self-healing, therefore, is not a one-off exercise but will need to take place repeatedly. At Cardiff University, we have been developing vascular networks that deliver healing agents to damage sites as and when they are needed, over the lifetime of a structure. We have also researched the use of novel shape memory polymers which can shrink or even completely close cracks when activated and we have worked with industry partners to monitor the long-term benefits of these new approaches.

Creating vascular networks

When the human body sustains an injury, the blood circulatory system springs into action, sending clotting agents to the wound, enabling tissue repair. Vascular networks in self-healing concrete work on the same principle, delivering healing agents when and where they are needed.

However, emulating this biological system in concrete structures poses a number of significant challenges. The vascular network needs careful design and manufacture if it is to encapsulate a range of healing agents, break open when required and do so with sufficient pressure to drive the agents out of the network and into the damaged zone. At Cardiff, we have developed one, two and three-dimensional vascular networks in the form of hollow channels within concrete elements. In addition, we have created single- and dual-channel three-dimensional printed polymer tetrahedral shaped mini-vascular network (MVN) units that can be readily deployed in concrete mixes. MVNs are designed so that a crack will rupture multiple tetrahedral ligaments, providing sufficient driving force for the release of the encapsulated prophylactic agents, overcoming some of the previously encountered shortcomings of cylindrical macro-capsules and closed-loop unpressurised vascular networks. We have explored different 3D printing materials and techniques to improve both the efficacy of the MVN healing system and the encapsulation of a wider range of healing agents.

Finding the right healing agent

The technology needs to be tailored to the type of damage it is likely to meet. For vascular networks, this means choosing the most effective healing agent: one with a long encapsulation life, which can flow into both large and small cracks, react in-situ and yield good bond strengths, all within the required healing timescales.

These criteria have driven our investigation into a wide range of commercial and novel research-based agents, combining those with long encapsulation lives, good reactivity and improved healing efficiency. We have tested many different types: one-part adhesives (cyanoacrylates) and resins; two-part epoxies and a range of silicate and lime-based healing agents. We have found flexural strength recoveries in excess of 100% for adhesive-based healing, whilst silicate-based healing agents have shown high stiffness recoveries.

We have shown that it is possible to achieve healing over multiple damage cycles, akin to repeated physical damage in structures, and that simultaneous damage and healing can occur under varying load rates. In addition, our investigations into modified cyanoacrylates, alternative silicate formulations and combinations of nano lime and nano silica have proved promising. Throughout this programme, it has always been our aim to combine different technologies where appropriate. In this instance, we have brought together a crack closure system with vascular networks in order to deliver a special type of flexible crack sealing agent.

Using shape memory polymers to close cracks

Limiting the width of cracks or even closing them once they appear, is an important part of the self-healing process in concrete structures. To enable this, Cardiff University and the University of Bradford have exploited the shrinkage potential of shape memory polymers (SMP) in fibre form and in a novel healing system comprising pre-tensioned hybrid tendons.

Polymers consist of long chain molecules – macromolecules – that, in normal conditions, are randomly arranged, coiled up and entangled with one another. Above a certain temperature, a polymer can be stretched mechanically by many times its own length, so that the molecules are straightened out and aligned in the direction of stretching. The polymer then acts like a rubber and will spring back to its original shape if released.

However, if the polymer is held in the stretched shape while its temperature is lowered, the aligned state of the molecules – the molecular orientation – can be frozen in place. Such a polymer will have improved stiffness and strength relative to the original unstretched material. However, researchers in this field were always aware that, in some cases, the oriented polymer products could begin to shrink back to their original pre-processed shape if they were raised in temperature, with a subsequent degrading of their mechanical properties. This phenomenon came to be recognised as useful, and the term 'shape memory polymer' (SMP) was devised.

For the RM4L programme and M4L grant, shape memory fibres were produced and optimised by the University of Bradford to achieve maximum shrinkage force. Devices consisting of bundles of fibres – 'tendons' – were made to produce high shrinkage force, and electrical heating was incorporated into the tendons to remotely trigger the shape memory response. The tendons were proven experimentally to be an effective means of crack closure. Tens of kilometres of fibres were manufactured and tested during the course of the projects.

The 'hybrid tendon' device takes the form of a hollow SMP tube with a prestressed Kevlar inner core along its central axis. When embedded within a structure and activated by heat, these tendons can generate sufficient compressive stress to close cracks and promote autogenic healing. Before installation and activation, the SMP tube is itself under compressive stress, and must be sufficiently strong and stiff to resist deformation. These properties are modified through the tube production process.

An alternative polymer-glass-fibre-based reinforcement (Tetcrete), created using injection moulding techniques, has also proven effective in achieving distributed micro-cracking within a concrete element and the formation of a material with a clearly defined post-peak strain hardening behaviour.

Concrete mixes designed to offer an enhanced autogenic healing response to damage have been coupled with the SMP hybrid tendons and Tetcrete and

TOP
Experimental testing of hybrid tendons. Credit: Cardiff University

ABOVE
Single and dual channel mini-vascular networks. Credit: Cardiff University

have demonstrated that healing can be achieved in a low-cement (low-carbon) concrete with high volumes of pozzolanic material.

Collaboration across the wider RM4L team has allowed the scale-up of a number of healing systems. A production line for hybrid tendons and a bespoke injection mould for Tetcrete reinforcing units have been established at the University of Bradford. The availability of a large quantity of Tetcrete units enabled us to construct a set of site trial Tetcrete structures at Cardiff University. These structures, which included a novel sensing system developed at the University of Bath, will continue to be monitored beyond RM4L and provide a unique insight into the long-term performance of the system.

Developing numerical models of self-healing systems

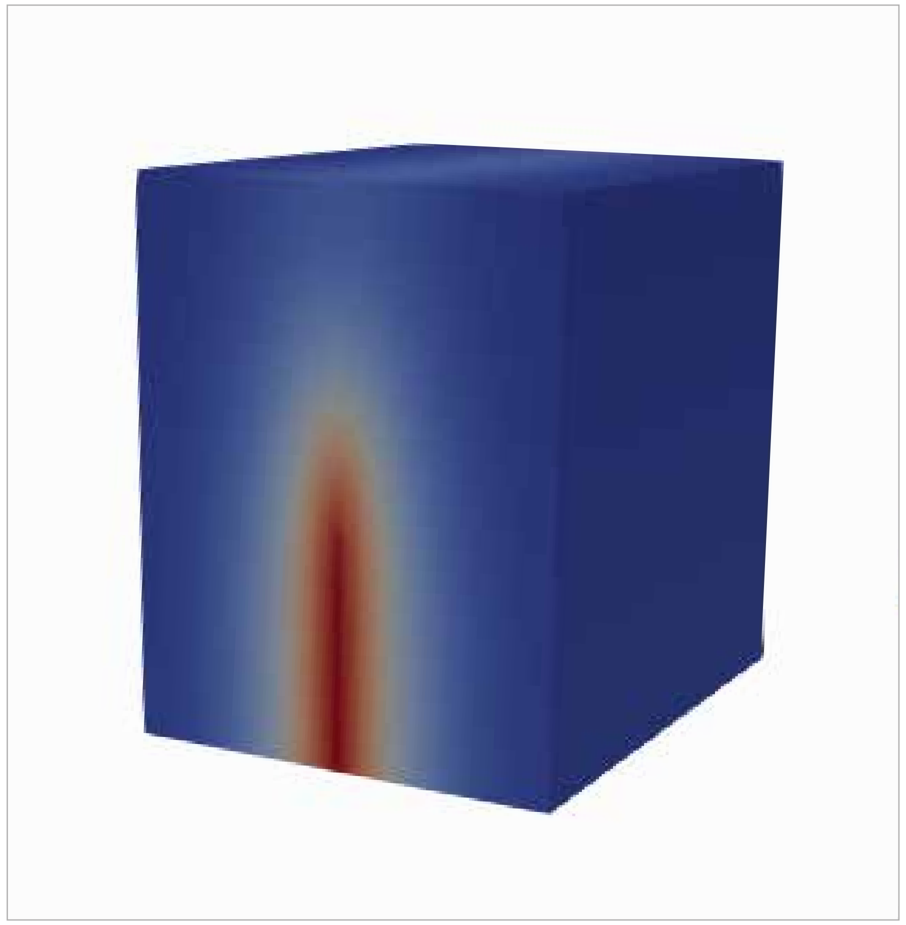
Alongside the development of self-healing technologies, Cardiff researchers have also developed numerical models which have given us the unique ability to successfully simulate and predict the performance of our novel self-healing systems. These will be used to inform the design and application of future healing agents and systems. The models have been tailored to specific healing systems in close collaboration with the experimental researchers.

The primary two- and three-dimensional finite element model has been extensively validated for autonomic vascular systems. The coupled three-dimensional model employs elements with embedded strong discontinuities linked to a damage-healing constitutive model component for mechanical behaviour. This is coupled to flow models that simulate healing-agent transport.

Moreover, through consideration of reactive chemical transport processes within the model, it has also been validated for natural autogenic healing in cementitious elements. The model has been used in blind predictions of a vascular autonomic system to determine which healing agent properties will be most effective and to identify possible new formulations. The model can be used to design and analyse structures formed from self-healing cementitious materials and is capable of being extended to include a wider range of self-healing systems, as explored by our partner universities.

Measuring the benefits

Alongside the experimental, modelling and design work, we have been working closely with our industry partners to consider the environmental life-cycle assessment (LCA) of our self-healing technologies. The ability to fully capture the long-term durability and performance benefits of biomimetic materials in the LCA is an ongoing research challenge; nevertheless, there is already clear evidence of the benefits self-healing concrete can bring to a wide range of applications.



TOP
Simulation of crack filling process.
Credit: Cardiff University

ABOVE
Casting large-scale Tetcrete culverts.
Credit: Cardiff University

RIGHT
Large-scale Tetcrete culvert trials.
Credit: Cardiff University

Capsules, continuous vascular networks and mineral additives

Encapsulation is when a healing agent is inserted into an outer coating to create a capsule. These capsules are then added to cement. When a crack occurs, the capsule's outer shell breaks, releasing its cargo which sets about repairing the damage.

Like all the RM4L biomimetic technologies, encapsulation is inspired by the way in which biological systems manage the behaviour of, for example, individual cells, hormones and antibodies. The University of Cambridge RM4L team has used this concept to develop a range of different encapsulation systems to solve a number of challenges.

Optimising microcapsules

The first encapsulation system we developed, in collaboration with industry partners Lambson and then Micropore, was in the form of microcapsules around 300-600 microns in size. These were made using complex coacervation with a gelatine/gum arabic shell and a sodium metasilicate core, as 40% emulsion in mineral oil. The advantages of this system were that the shell was sufficiently flexible to not disintegrate during the vigorous concrete mixing process. Then, as the cement set and hardened, the shell became brittle through loss of water, making it easy to break open when the cementitious matrix cracked.

The sodium metasilicate core was chosen as it is a common repair grout and was able to seal certain crack sizes within a period of a week or two. Lambson was able to scale up the production of these microcapsules providing a 75 kg batch which was initially used in full-scale field trials followed by two commercial applications. The dosage and performance was optimised for different cementitious mixes and applications scenarios. More recently, working with Micropore, we encapsulated linseed oil to target corrosion-related damage. The effectiveness of combining both types of microcapsules to address physical and chemical damage was the subject of unique large-scale laboratory tests towards the end of the programme grant.

Using microfluidics for precision engineering

In parallel, we set up a microfluidics system to produce monodispersed capsules and to help with fine-tuning and further developing the functional properties of capsules. Microfluidics is a powerful platform for exploring a range of shell materials and cargos with precision, in a way that is not possible with traditional stirred tank systems. It allowed us, for example, to explore the development of pH-sensitive shells as well as microcapsules containing 100% sodium silicate core.

FAR LEFT
Sodium metasilicate microcapsules embedded in a cementitious matrix.
Credit: University of Cambridge

ABOVE
Self-healing and self-sensing laboratory-scale beam.
Credit: University of Cambridge

Scaling up using membrane emulsification

Complex coacervation is mainly used for industrial-scale manufacturing: we wanted to establish a laboratory scale-up system for microcapsule fabrication. We were able to achieve this through the novel technique of membrane emulsification, an expertise unique to Micropore. Membrane emulsification enables the rapid and large-scale production of microcapsules in a way that is also significantly more sustainable, uses less energy and produces less waste than other encapsulation techniques. Through membrane emulsification we were also able to explore, together with Micropore, the large scale production of microcapsules containing linseed oil.

Smart aggregates

Capitalising on the practical as well as the sustainability credentials of lightweight aggregates (LWA), including waste-based types, we also produced larger capsules, 2 to 9 mm in diameter, that could be used to replace the coarse aggregate components within concrete. We impregnated a range of LWAs (Lytag, expanded clay and pumice) under vacuum using the same cargos described above, and coated them with polyvinyl alcohol (PVA) to produce self-healing capsules. Around 30% substitution by volume resulted in a good self-healing performance in large one-metre long beams cured in a saline environment.

Corrosion inhibiting mineral additives

Advancing recent developments in chloride binding mineral additives, we embarked on the synthesis of minerals such as hydrotalcites that are intercalated with different corrosion inhibitors. The aim was to provide not only a mechanism to capture the chlorides as they migrated into the concrete cover zone, but also to release those corrosion inhibitors to protect the steel reinforcement against corrosion initiation. We were able to do this at laboratory-scale and produce a proof of concept.

Healing through vascular networks

For types of damage that need larger volumes of healing agents and for dealing with repeated damage, we focused our efforts on the design and delivery of vascular systems that mimic the flow of blood through veins. We designed a number of two- and three-dimensional configurations with varying bifurcations and channels sizes that obeyed Murray's Law for blood flow. The two-dimensional designs were suitable for incorporation within the cover zone or as a surface overlay and the three-dimensional patterns were designed to enable hierarchical structures in the vicinity of the reinforcement. We also experimented with polymer-graphene composites as the wall materials to enable self-sensing capabilities and explored self-healing polymer composites for repeated healing.

Low-carbon cement and concrete

Much of our work has been carried out within the context of low-carbon cementitious systems, using different mix compositions and formulations depending on the application. Life-cycle and cost analysis were also carried out to show how the technologies can reduce the carbon footprint of infrastructure both by extending its life and by reducing the amount of cement and concrete used to build it.

Large-scale laboratory trials

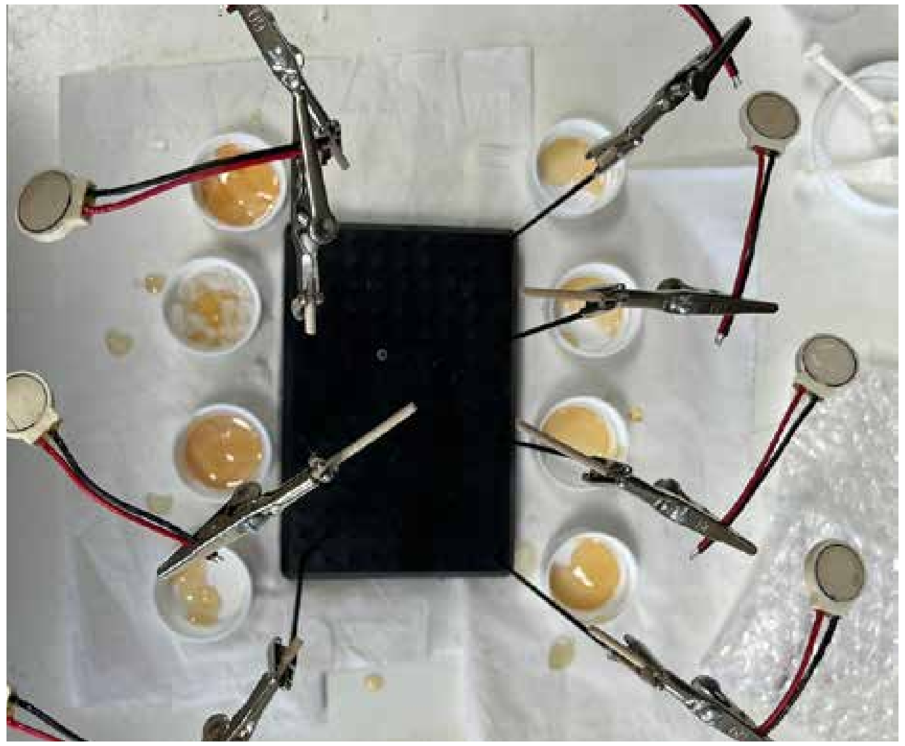
The work described above represents just a few examples of the biomimetic materials and products that we successfully explored and developed throughout the five years of the programme grant.

While much of our previous large-scale testing focused on dealing with physical damage in the form of surface cracking, towards the end of the RM4L programme we were able to extend this to test a combination of physical and chemical damage using the range of our developed products.

Our work at Cambridge has culminated in large-scale laboratory trials in which we constructed more than 20 beams, each a metre long, using more than 10 different biomimetic materials and products. The specimens, made with low-carbon concrete, were instrumented with a range of commercial and developed sensors, as well as self-sensing coatings, which meant we could continuously monitor and record the behaviour of each sample. The sensors measured temperature, humidity, strain, electrical resistivity and electrochemical potential. The damage was initiated through forced corrosion of the rebars which resulted in internal cracking. Such damage is one of the scenarios which often goes undetected and has led to catastrophic failures, as in the case of the Morandi Bridge in Italy.

Benefits across the life-cycle

Throughout RM4L, we demonstrated the many benefits of deploying self-healing and self-sensing materials. Life-cycle analyses enabled us to demonstrate the environmental benefits and reduced emissions during the service life of the products. The versatility of the materials and products we developed and their successful incorporation into a range of low-carbon concretes means that we are able to reduce both their embodied and operational carbon, leading to a significantly lower carbon footprint than current materials.

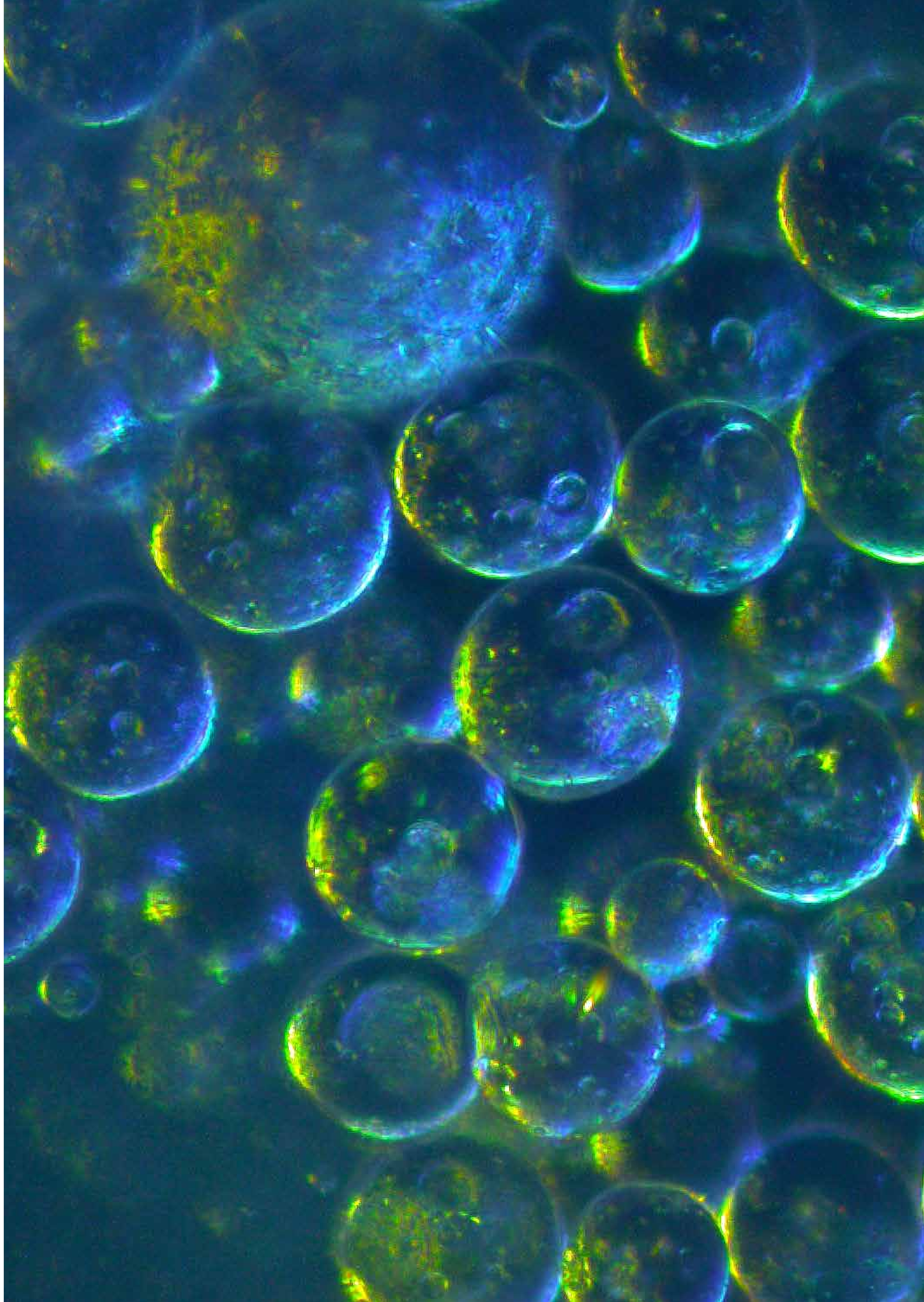


We have also demonstrated the versatility, reliability and durability of these systems. The research at the University of Cambridge successfully developed a range of products that were able to target a wide range of damage scenarios and which were tailored to a number of different applications. This opens up huge possibilities for the application of those materials and products in our future infrastructure as it braces itself to become more resilient and sustainable in the face of climate change.

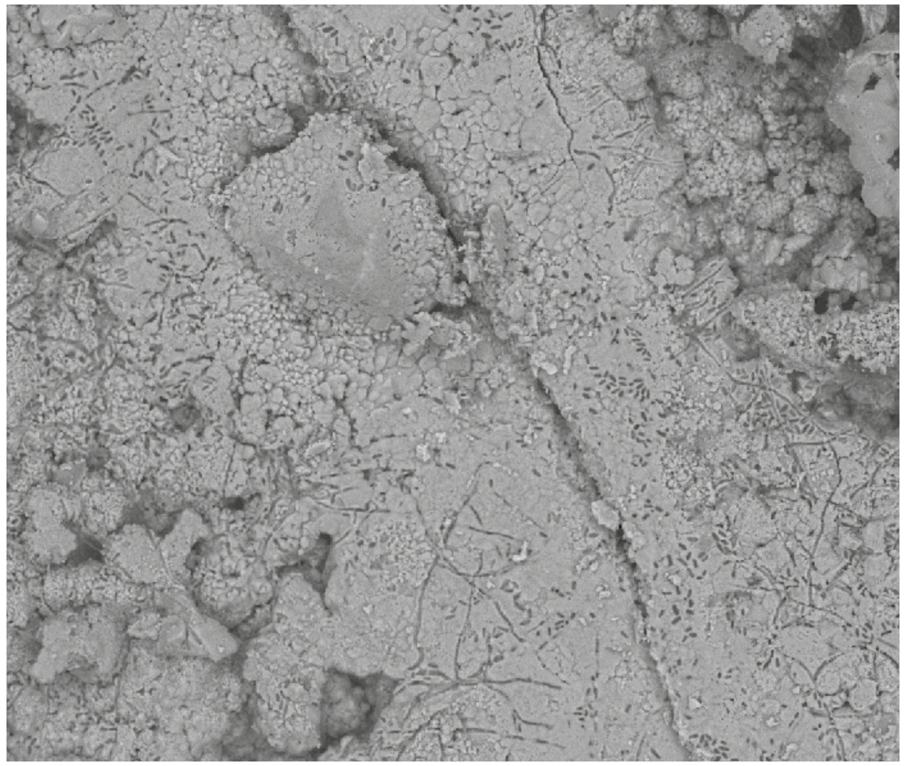
TOP
Piezoelectronic sensors for self-sensing within cementitious materials.
Credit: University of Cambridge

ABOVE
3D printed vascular networks designed to obey Murray's Law.
Credit: University of Cambridge

RIGHT
Membrane emulsification microcapsules.
Credit: University of Cambridge



Bacteria for self-healing concrete



Why bacteria?

Bacteria are some of the most interesting organisms on this planet. They can be found everywhere, even in places as inhospitable as volcanoes, acidic hot springs and Antarctica. Furthermore, our landscape and many geological features, including stalactites, stalagmites and stromatolites, have been formed by bacterial activity.

Researchers are now realising that these natural processes can be exploited in several biotechnological applications. One such process is microbial-induced calcite precipitation, which has been used by the University of Bath to produce bacteria-based self-healing of concrete.

Such self-healing concrete is achieved by embedding durable forms of bacteria called 'spores' within the concrete and providing them with the nutrients they need to grow. While the bacteria are in their spore form, they are inactive. However, when cracks appear in concrete, the entry of water and oxygen provides favourable conditions for the spores to germinate into active cells and multiply.

A key aspect of work at Bath through RM4L has been to optimise bacterial growth and healing ability in a number of different environments that reflect real-world settings and applications. Developing a self-healing concrete that can work in many different settings requires a multi-disciplinary team of the kind found at Bath, comprising microbiologists, concrete technologists and civil engineers.

Finding the right species

The use of bacteria to achieve healing in any application will always depend on the exposure conditions one might be expected to find. Before RM4L, little attention had been paid to such details, with the focus being on optimum conditions for bacterial species that do well at alkaline pH, as is found in concrete, and, in particular, those that grow well in laboratory conditions, for example at above 25°C. However, in real life, concrete structures are exposed to more extreme ambient conditions, which means the bacteria need to thrive in much cooler conditions or when exposed to high salinity. To address these challenges, we needed to find new bacteria.

Fortunately, Bath lies in a part of the country where bacteria that like such conditions can be readily obtained from nearby limestone caves and marine sediment deposits. Indeed, by not going too far afield we have isolated appropriate environmental bacteria from the areas around Cheddar Gorge, and from a nearby bat cave. We surveyed these environmental bacteria for their ability to precipitate calcium carbonate under a range of stressful conditions. This has resulted in a unique library of over 130 calcite-precipitating bacteria capable of working in a wide range of environments.

Getting the bacteria into the concrete

When we add the bacterial spores to concrete, we generally encapsulate them in aerated concrete granules and then coat these granules with polyvinyl acetate. This encapsulation protects the spores from being crushed during the hardening of the concrete. However, we have also explored other approaches and have shown that it could be simpler and cheaper to protect the spores in air bubbles using air-entrainment admixtures commonly used by the concrete industry.

Extending their application

By using an appropriately encapsulated bacterium, we can obtain self-healing of concrete in a range of conditions many of which had not previously been demonstrated, including at early age (28 days), at later ages (22 months), following carbonation, in cold conditions (7.5°C) and in wastewater (in collaboration with Newcastle University).

The ability of bacteria to precipitate calcite in aged and carbonated concrete has been a unique aspect of research at Bath. For bacteria to precipitate calcium carbonate in cracks they need the presence of dissolved inorganic carbon and calcium ions. For this reason, a growth medium containing both carbon and calcium is normally added simultaneously with the spores during mixing. However, a fundamental question that has divided researchers of bacteria-based self-healing around the world is whether this growth medium should be added directly to the concrete as a powder or whether it also needs to be encapsulated. We have shown that if concrete is allowed to carbonate before it is cracked, then the calcium in the growth medium will become locked up and cannot be used by the bacteria. Consequently, the answer is clear. If the concrete is likely to carbonate, calcium should be encapsulated so that it is only available when the crack is formed and not earlier.

"Such self-healing concrete is achieved by embedding durable forms of bacteria called 'spores' within the concrete and providing them with the nutrients they need to grow. "

Creating a bacteria mix for a variety of applications

In general, there is no single solution for bacteria-based self-healing concrete and the bacteria, growth media and encapsulation technologies must be specifically chosen for each application. The ability to select appropriate bacterium is not in the knowledge set of most concrete engineers.

Therefore, we have been looking to create a simpler mixture of bacteria for use in a wide range of common conditions, such as extreme temperatures and even perhaps saline

LEFT
Calcite precipitation over a concrete crack showing bacterial footprints.
Credit: University of Bath

ABOVE
Bacterial colonies on an agar plate.
Credit: University of Bath

conditions. This is more complicated than it might appear, as bacteria do not tend to be particularly friendly with one another and finding a harmonious mixture of bacteria is tricky.

Genetically engineering a single bacteria solution

This led to us to investigate whether it would be possible to engineer a single bacterium to be suitable for a wider range of environments by introducing novel genetic "calcite precipitation modules" into weak calcite precipitators. That is, take bacteria that are poor at calcite biomineralisation, but which otherwise perform very well at low temperatures and in saline conditions, and modify their genes to make them capable of self-healing concrete.

We have succeeded in showing that we can take the laboratory bacterium *Bacillus subtilis* W168, which does not ordinarily precipitate calcite and make it do so through genetic engineering. Whilst it may not be practical to use genetically engineered bacteria in real-world applications, what this has given us is a more fundamental understanding of how and why calcite precipitation occurs, and what we need to do to improve the performance from environmental species.

Benefits across the life-cycle

Alongside this experimental research, we have been undertaking environmental life-cycle assessments to demonstrate that the extra effort required to make concrete self-healing leads to long-term benefits across the whole life cycle. Overall, we have demonstrated that bacteria-based self-healing of concrete is a reliable and useful technology for maintaining the durability and resilience of our infrastructure. Research at Bath through RM4L has solved several fundamental and application-related challenges, and we can look forward to a future world in which bacteria are routinely added to concrete as a means of providing self-healing.

0-Days (Post-cracking)

28-Days (Healing)

TOP
Collection of environmental samples for isolation of calcite precipitating bacteria.
Credit: University of Bath

ABOVE
Progression of microbial-induced healing of cracks in cementitious mortar.
Credit: University of Bath

Sharing the research
RM4L International Conference

71
delegates from 16 countries

61
papers presented by researchers from 24 universities in 14 countries

7
industry representatives

The RM4L conference took place online in September 2021. Its focus was deliberately broad, aimed at encompassing the full gamut of smart construction materials that can adapt themselves to a changing environment.

It achieved good levels of attendance from researchers around the world in a variety of different disciplines and from a good range of industry partners.

A number of academic publishers awarded prizes, which helped to increase the range of publications to which papers were submitted. Three best paper prizes were awarded by *Applied Sciences* and two by the journal *Sustainability*.

Reflections on the conference
Bob Lark, Emeritus Professor, Cardiff University

"Papers were presented on a wide range of techniques and materials, some simple to implement, others more sophisticated, both with their merits. While simpler solutions would seem to be easier to deploy, the more scientifically complex are enabling the sector to make important conceptual advances."

"The multidisciplinary nature of the conference was also very stimulating. Coming at problems from different perspectives is important to challenge preconceptions. For example, a paper on using robots to deploy smart materials highlights the need to think about completely different properties that such materials will need to be manufactured with in the future."

"For me, the industry session was a highlight. We had a productive discussion with excellent input from our industrial partners. Although we are seeing some valuable developments in smart, self-healing construction materials, there are still many barriers that need to be overcome if these developments are to have real-world impact."

"Their true value will not be realised if we merely replace existing materials with new ones. Self-healing technologies should extend the life of our structures and reduce their carbon footprint. But it is only by fundamentally rethinking how we conceive and design new infrastructure that we will be able to fully harness the benefits of these smart materials."

The conference was co-sponsored by a number of key industry and research bodies: RILEM, Institution of Civil Engineers, Institute of Materials, Minerals and Mining, the Institution of Structural Engineers, the Concrete Society, American Concrete Institute, Institute of Concrete Technology, MDPI and Applied Sciences.

Meet the team

6
Principal Investigators

13
Co-Investigators

24
RM4L postdoctoral researchers

31
aligned researchers

Professor Tony Jefferson

Department of Civil Engineering, School of Engineering, Cardiff University

Principal Investigator, Programme Grant Director and Chair of the PGMB

April 2017 – October 2022

Overall responsibility for RM4L and chair of the management board, working closely with the lead investigators from partner universities, industrial collaborators and external scientific board. Involved in work on mini-vascular networks and hybrid tendons and led two modelling-focused work packages.

Professor Bob Lark

Department of Civil Engineering, School of Engineering, Cardiff University

Former Principal Investigator, Chair of the RM4L International Conference

April 2017 – August 2018

Now: retired

RM4L's first PI. Research into shape memory polymer self-healing systems and active in engaging with industry on the design and deployment of these systems in practice.

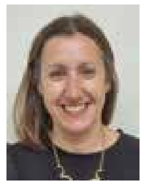
Professor Abir Al-Tabbaa

Department of Engineering, University of Cambridge

Principal Investigator for the University of Cambridge and Programme Grant Director

April 2017 – October 2022

Director of RM4L and member of its management board. Led research into microcapsules, macrocapsules, vascular networks, smart fibres, smart additives, sensors and self-sensing materials as well as scale-ups, field trials and commercial deployment. Applications spanned the breadth of infrastructure materials from cemented-soils to concrete.



Dr Diane Gardner

Department of Civil Engineering, School of Engineering, Cardiff University

Co-Investigator and Programme Grant Director

April 2017 – October 2022

Director of RM4L and member of its management board. Research on active additives for the catalysis of healing agents and scaling up of the Tetcrete technology and led the development and testing of mini-vascular networks.

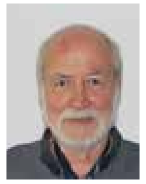
Professor Kevin Paine

Department of Architecture and Civil Engineering, University of Bath

Principal Investigator for the University of Bath and Programme Grant Director

April 2017 – October 2022

Director of RM4L and member of its management board. Led research into the development of bacteria-based self-healing concretes for use in realistic environments and the development of concretes that can sense cracks and trigger an appropriate response.



Professor John Sweeney

Interdisciplinary Research Centre in Polymer Science and Technology

Principal Investigator for the University of Bradford

April 2017 – October 2022

Led on developing and manufacturing polymer-based devices to close cracks in concrete for self-healing structures.

Dr Richard Ball

Department of Architecture and Civil Engineering, University of Bath

Co-Investigator

April 2017 – October 2022

Research into self-sensing concrete materials that can detect damage.

Dr Richard Cooper

Department of Biology & Biochemistry, University of Bath

Co-Investigator

April 2017 – March 2018 (died October 2018)

Led the microbiology work in RM4L re-examining the cultures used in M4L for their applicability to the more demanding concretes proposed by RM4L. Brought new members of the microbiology team up-to-date in the use of bacteria in self-healing concrete.

Dr Robert Davies

Department of Civil Engineering, School of Engineering, Cardiff University

Co-Investigator

April 2017 – July 2021

Now: Principal Engineer, Arup

Research into crack closure and vascular systems, while also contributing to the self-sensing collaboration. Led on numerical modelling, laboratory scale testing and developing plans for upscaling technologies alongside industry partners.

Professor Susanne Gebhard

Department of Biology & Biochemistry, University of Bath

Co-Investigator

April 2017 – October 2022

Research into bacteria that can be used in self-healing concrete and using synthetic biology to engineer the ability to form calcite minerals into a laboratory bacterium.

Dr Mike Harbottle

Department of Civil Engineering, School of Engineering, Cardiff University

Co-Investigator

April 2017 – October 2022

Research into biological self-healing, particularly in geo-materials (soils and rock) as well as cementitious composites.

Professor Andrew Heath

Department of Architecture and Civil Engineering, University of Bath

Co-Investigator

April 2017 – October 2022

Research into concrete materials and the engineering aspects of bacterial self-healing concrete.

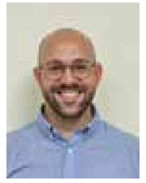
Professor Gopal Madabhushi

Department of Engineering, University of Cambridge

Co-Investigator

April 2017 – October 2022

Research into fibre-reinforced engineered cementitious composites designed to self-heal under cyclic loading. Also involved in research into self-healing soil-cement systems subjected to aggressive chemical attack as a result of ground contamination.



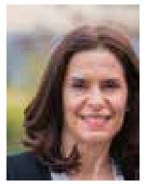
Dr Riccardo Maddalena

Department of Civil Engineering, School of Engineering, Cardiff University

Co-Investigator, Programme Grant Coordinator, former postdoctoral researcher and Programme Grant Manager

April 2017 – October 2022

Project Manager responsible for organising and coordinating the annual RM4L forums, the conference and a series of outreach events and professional development workshops for our researchers. Research on self-healing technologies and life-cycle assessment.



Professor Athina E. Markaki

Department of Engineering, University of Cambridge

Co-Investigator

April 2017 – October 2022

Research into different 3D hierarchical vascular systems, manufactured using 3D printing and embedded in cementitious materials to allow healing agents to be routinely replenished.

Professor Laura Torrente

Department of Chemical Engineering & Biotechnology, University of Cambridge

Co-Investigator

April 2017 – October 2022

Research into envisioning of a novel membrane and working with Micropore on an emulsification rig for the production of microcapsules.

Dr Iulia Mihai

Department of Civil Engineering, School of Engineering, Cardiff University

Co-Investigator

June 2018 – October 2022

Research focused on the modelling aspects of RM4L, in particular simulating the behaviour of self-healing fibre-reinforced cementitious materials.

Dr Alison Paul

School of Chemistry, Cardiff University

Co-Investigator

June 2018 – October 2022

Research into the synthesis and characterisation of nanoparticles designed as active additives in self-healing concrete.

Dr Brunella Balzano

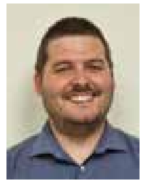
Department of Civil Engineering, School of Engineering, Cardiff University

Postdoctoral researcher/Co-Investigator

April 2018 – July 2020: postdoctoral researcher

July 2020 – October 2022: Co-Investigator

Research into hybrid tendons, a concrete crack-closure technology. Adapted design codes to include the use of self-healing technologies and combined concrete 3D-printing with self-healing technologies.



Dr Brubeck Lee Freeman

Department of Civil Engineering, School of Engineering, Cardiff University

Postdoctoral researcher

April 2017 – October 2022

Research into numerical models for predicting the behaviour of the self-healing materials.

Dr Chrysoula Litina

Department of Engineering, University of Cambridge

Postdoctoral researcher

April 2017 – February 2021

Now: Principal Research Engineer, National Highways

Research into microencapsulation and vascular technologies for self-healing materials using traditional and new manufacturing techniques as well as characterisation and up-scaling. Led the first commercial application of microcapsule-based self-healing concrete on site in West Cambridge.

Glen Thompson

Interdisciplinary Research Centre in Polymer Science and Technology, University of Bradford

Specialist Process Technician

April 2017 – October 2022

Lead technical researcher at Bradford, developing and manufacturing polymer devices for the project.

Dr Cristina Tuinea-Bobe

Faculty of Engineering and Informatics, University of Bradford

Postdoctoral researcher

April 2017 – October 2022

Project management and involved in manufacturing shape memory polymers (SMP) and spheritet material selection, characterisation and manufacturing.

Dr Bianca Reeksting

Department of Biology and Biochemistry, University of Bath

Postdoctoral researcher

August 2017 – October 2022

Research into environmental bacteria that can survive the adverse conditions found in concrete.

Dr Efi Tzoura

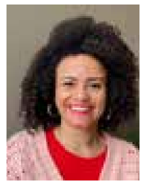
Department of Architecture and Civil Engineering, University of Bath

Postdoctoral researcher

October 2017 – October 2018

Now: Innovation Manager, Ferrovial UKI

Research into the design and procurement of the piezosensors that were used for the self-sensing of concrete throughout the RM4L project.



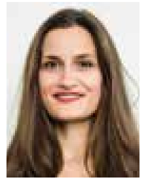
Dr Lívia Ribeiro de Souza

Department of Engineering, University of Cambridge

Postdoctoral researcher

November 2017 – September 2022

Research into microcapsules using microfluidics for self-healing in cementitious materials and bio-based shells to promote greener chemistry. Explored the use of composites with carbon nanofibers to promote self-sensing properties.



Dr Magdalini Theodoridou

Department of Civil Engineering, School of Engineering, Cardiff University

Marie Skłodowska-Curie Research Fellow

January 2018 – January 2020

Now: Newcastle University Academic Track (NUAcT) Fellow, Hub for Biotechnology in the Built Environment, School of Engineering, Newcastle University

Research into using bacteria commonly found in soils to repair bulk materials (such as natural stone) or already hardened composites (such as lime-based mortars) in areas particularly prone to weathering.

Dr Cristina De Nardi

Department of Civil Engineering, School of Engineering, Cardiff University

Postdoctoral researcher

July 2018 – October 2022

Research into vascular and mini-vascular networks (MVNs) for use in both self-healing concrete structures and in biomimetic systems for the preservation of historic buildings.

Dr Hussameldin M. Taha Abdalgadir

Department of Architecture and Civil Engineering, University of Bath

Postdoctoral researcher

November 2018 – April 2022

Now: Industrial Research Fellow, Costain Group

Research into damage detection and repair in cementitious structures using smart piezoceramic sensors.

Dr Rami Alghamri

Department of Engineering, University of Cambridge

Yousef Jameel Foundation Fellow

June 2019 – August 2021

Now: Project Manager, United Nations Relief and Works Agency (UNRWA)

Research into self-healing waste-based lightweight aggregates impregnated with healing agents and developed a proof of concept using large laboratory-scale trials of concrete beams. Developed quantitative 3D models to optimise the aggregates dosage for crack healing.

Dr Regeane Bagonyi

Department of Engineering, University of Cambridge

Postdoctoral researcher

August 2019 – July 2021

Now: Data Product Manager, Pivigo

Research into the performance of self-healing cementitious systems using computational modelling and applied machine learning algorithms to experimental results. Led the production of polymer-graphene fibre composites for self-sensing applications in cementitious systems and investigated methods of minimising corrosion-induced damage.

Dr Amir Zomorodian

Department of Engineering, University of Cambridge

Postdoctoral researcher

August 2019 – April 2021

Now: Materials Scientist at Renishaw PLC

Research into electrochemical testing systems for the evaluation of corrosion mechanisms in reinforced cementitious materials and the development and characterisation of novel and green corrosion inhibitors (both organic and inorganic).

Dr Ismael Justo-Reinoso

Department of Architecture and Civil Engineering, University of Bath

Postdoctoral researcher

December 2019 – October 2022

Research into bacteria-based self-healing technology: novel encapsulation methods, cyclic healing using mini-vascular networks and life-cycle assessments.

Dr Sripriya Rengaraju

Department of Engineering, University of Cambridge

Postdoctoral researcher

March 2021 – September 2022

Research into novel corrosion inhibitors and smart aggregates. Led the team activities on the life-cycle assessment of our innovative materials to understand their environmental footprint and their contribution to our net zero commitment.

Dr Muaaz Wright-Syed

Department of Civil Engineering, School of Engineering, Cardiff University

Programme Grant Manager/ postdoctoral researcher

June 2021 – January 2022

Now: Environmental Consultant, Frith Resource Management

Upscaling of self-healing technology and day-to-day management of the programme grant.

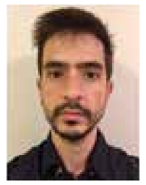
Dr Vahid Afroughsabet

Department of Engineering, University of Cambridge

Postdoctoral researcher

July 2021 – August 2022

Research into self-sensing, self-healing cementitious materials using smart fibres and the development of self-healing low carbon concrete pavement as well as large-scale laboratory trials at Cambridge.



Dr Christos Vlachakis

Department of Engineering, University of Cambridge

Postdoctoral researcher

October 2021 – September 2022

Research into geopolymer-based low carbon self-sensing cementitious coatings for concrete monitoring. Took part in the fabrication and testing of large laboratory-scale self-healing concrete beams with different self-healing and self-sensing systems for long-term monitoring.

Dr Kumaran Coopamootoo

Department of Civil Engineering, School of Engineering, Cardiff University

Postdoctoral researcher

October 2021 – May 2022

Now: Postdoctoral researcher, Princeton University

Research into the effectiveness of different types of mini-vascular networks (MVNs).

Dr Yen-Fang Su

Department of Engineering, University of Cambridge

Postdoctoral researcher

December 2021 – July 2022

Now: Assistant Professor, Louisiana State University, USA

Research into machine learning model for predicting the self-healing performance of mineral additive-based self-healing concrete. Developed a novel sensing method for monitoring concrete healing/damage monitoring.

Alex Bradley

Department of Civil Engineering, School of Engineering, Cardiff University

Postdoctoral researcher and RM4L Project Manager

April 2022 – October 2022

RM4L Project Manager, organising and coordinating regular PGMB meetings, the annual RM4L researchers' forum, and the final RM4L event.

Peter Adesina

Department of Architecture and Civil Engineering, University of Bath

Postdoctoral researcher

July 2022 – October 2022

Research into the effectiveness of microbial-induced calcite precipitation for civil engineering applications.

Trialling the technologies

Carrying out trials was an important aspect of both M4L and RM4L to show how their emerging technologies would perform in real-world settings. They also helped us to understand the challenges that need to be overcome in order to achieve deployment at commercial scale.

M4L Heads of the Valley site trial

The large-scale site trial of self-healing concrete carried out in 2015 as part of M4L was the first of its kind in the UK. It took place as part of a major upgrade by the Welsh Government to the 'Heads of the Valley' section of the A465 in South Wales. The research team worked closely with the lead contractor, Costain, throughout.

A series of retaining walls were built near to – but separate from – the main construction site. In this way, they did not interfere with the main works but were exposed to the same conditions and built using the same processes. Each wall was used to test a particular self-healing technique or combination of techniques: microcapsules, bacteria, shape memory polymers and vascular networks. The walls were mechanically cracked after 35 days of curing and then reloaded and monitored for self-healing over a six-month period using air permeability, crack depth and microscopic crack width measurements.

Overall, the trial demonstrated that all four technologies could be deployed in a 'real-world' setting, with the physical implementation proving to be a relatively straightforward process. It also showed that all the technologies were sufficiently promising to warrant further research. It also clearly demonstrated that different techniques are better suited to dealing with different types of damage – an insight that underpinned the design of the RM4L programme.

Trialling microcapsules at Cambridge

In 2017, work started in Cambridge on the construction of a new, purpose-built Department of Civil Engineering. This was an ideal opportunity for the Cambridge RM4L team, working in close collaboration with the contractor, SDC, to trial self-healing microcapsule-based concrete, optimised following the lessons learnt from the Heads of the Valley trial, using the microcapsules produced by Micropore.

As part of the build, two external concrete slabs were designed and cast with two different dosages of the microcapsules. The self-healing additives were mixed into batches of ready-mix concrete on site and cast into slabs, using standard industry processes.

One of the challenges of using trial materials in a real-world setting is that they have to conform with industry standards, such as minimum compressive strength and workability. The Cambridge team was able to demonstrate compliance in all but one area, skid resistance, which it was unable to test for due to absence of the necessary equipment. By working closely with the contractor, the problem was solved by the addition of gravel aggregates to create a rough surface.

The performance of the slabs was closely monitored for 12 months in terms of density, compressive strength, durability and corrosion. The tests showed that the presence of microcapsules did not affect the practical strength development of the slabs. Longer-term analysis is needed to understand the effects on durability

Because the slabs were part of a real building, they could not be 'pre-cracked'. To test the self-healing properties of the material, the team cracked the small prisms which had been cast at the same time, of the same materials.

Close monitoring of these cracks confirmed that the microcapsule concrete showed a pronounced self-healing capability. This integration of microcapsule-based self-healing into a permanent structural application not only demonstrated the maturity of the technology and the ease with which it could be deployed through close collaboration with the contractor, it also offered invaluable insights into its performance.

Previously, in 2015, the construction of the James Dyson Building at Cambridge's Department of Engineering had also afforded the Cambridge team an opportunity to trial a range of cement-based materials. 200 lightweight concrete blocks were placed in non-structural sections of the plant room on the roof of the building. The blocks were manufactured at the Department from a wide range of innovative cements, aggregates and additives including self-healing concrete and 'clinkerless' cement concrete.

These blocks have been continuously monitored for their strength, permeability, surface resistivity and ultrasonic pulse velocity and, at seven years after construction, have demonstrated excellent performance.

Trialling bacteria-based self-healing concrete in a wastewater treatment plant

One of the potential uses for bacteria-based self-healing concrete is in water-retaining structures such as wastewater plants, reservoirs and concrete pipes, where cracking can cause leaks and, hence, significant maintenance challenges.

This trial tested the effectiveness of the technique at scale and how the bacteria would cope when used in an industrially relevant environment, and not the clean laboratory environment they had been developed in. Early results indicate that the bacteria respond well to the wastewater environment.

For this trial, the Bath team collaborated with Newcastle University and the trial itself was hosted by Newcastle's BEWISe experimental wastewater treatment facility operated by Northumbrian Water. Individual blocks of mortar, some including spores, and each with a crack of around 0.5 mm wide, were exposed to wastewater for more than two months and the crack healing was monitored every seven days. An identical set of blocks was exposed to tap water over the same period in the laboratories at Bath.

The preliminary findings look promising but the full data has yet to be analysed and published.

"Overall, the trial demonstrated that all four technologies could be deployed in a 'real-world' setting, with the physical implementation proving to be a relatively straightforward process."

Commercial deployment of microcapsule-based self-healing concrete.
Credit: University of Cambridge

Trialling novel polymers for self-healing

Working with the University of Bradford, Cardiff University has been trialling the behaviour of prefabricated culverts, made from 'Tetcrete', a concrete reinforced with polymer tetrahedral units.

The team cast three two-metre wide lightly reinforced concrete culvert sections. Two of these were formed with a Tetcrete concrete mix that had enhanced healing properties and the other was a standard concrete control structure. Approximately 3000 'Spheritet' units, manufactured at the University of Bradford, were embedded in each of the Tetcrete structures.At the same time, hundreds of smaller samples were cast in different forms – cubes, cylinders and prisms – which could be exposed to the same conditions but were easier to bring into the lab for analysis.

The main culverts were initially loaded to produce cracks of just over 0.2 mm and their tensile and compressive strengths were tested every 28 days. After the initial load had been applied, it was maintained over the period of the trial to see if the polymers would creep under a constant load. The trial was also designed to test other behaviour such as how quickly – and to what depth – surface water seeped into the specimens, as well as how the flexural strength of the Tetcrete composite material changed over time.

As well as working with the University of Bradford to develop the Spheritets, Cardiff also collaborated with the University of Bath on monitoring the culverts using Bath's novel piezoelectric sensing system. The intention is to continue monitoring the culverts for several more years. Once the analysis is complete, the site trial's findings will be used to look again at how we design Tetcrete structures based on a much better understanding of how the system behaves over time.

Towards commercial adoption
Industry collaboration and impact

Working hand in hand with industry partners has been at the heart of the RM4L programme from the outset. If new self-sensing, self-healing technologies are to realise their full potential, they need to address significant industry challenges and to be usable and effective at a commercial scale. To this end, RM4L has worked with more than 20 organisations from across the industry, including technical specialists involved in developing the new technologies, manufacturers, supply chain partners, engineering firms, national construction companies and government agencies.

The Industrial Advisory Board has provided guidance to the research team throughout. In addition, a number of industry partners have worked closely with researchers, sharing their knowledge and expertise in order to develop technologies that can make our buildings and infrastructure last longer at less cost, while reducing their environmental impact.

Micropore's membrane emulsification set-up. Credit: Micropore

Infrastructure company: Costain

Tim Embley
Innovation Director, Costain

Working with leading academics is an important part of our role. As an industry leader, we need to challenge existing thinking, accelerate new ideas and feed the innovation pipeline in a way that meets national and industry needs. Those needs include being able to extend the life of assets and to decarbonise those assets by reducing the number of interventions we need to maintain them.

As well as playing a key role on the IAB, helping to ensure RM4L research was focused on delivering commercial impact, Costain has been involved in demonstrating and testing the technologies in live environments. These collaborative activities both informed the research while giving us new insight into how this science could be applied in the 'real world' and how we might need to change as an industry to do so. For example, we need to rethink the processes we use to deploy advanced materials, an issue which aligns with industry ambitions for automation, increased productivity, efficiency, sustainability and carbon neutral outcomes.

Some of the technologies emerging from RM4L look very promising, particularly the work on encapsulation and coating materials. Another area of interest for us is the use of sensor technologies combined with advanced materials so that we can measure and understand how they perform in the real world.

Our involvement with RM4L has undoubtedly helped to advance Costain's strategic position on decarbonisation. We have seen first-hand the emergence of new technologies and understood how they could be made available to our engineering teams. This has helped us think about how we can accelerate our net zero agenda to meet our 2045 targets.

Our interest in RM4L technologies continues through our involvement in the Digital Roads of the Future Programme with the University of Cambridge.

Technology company: Micropore Technologies

Dave Palmer
Operations Manager, Micropore Technologies

Micropore Technologies designs and manufactures devices which, by using a technique called membrane emulsification, can be processed into microcapsules which can act as targeted delivery systems. As a spin-out from Loughborough University, we value the interactions between academia and industry, so we were very pleased to become involved in RM4L.

The collaboration has allowed us to design and develop new encapsulation systems, specifically for self-healing in cementitious systems. Getting involved in the specific requirements of the construction industry was a new challenge for us, particularly dealing with the high pH of the cement matrix and the aggressive mixing environment.

Designing a capsule system to a brief is standard practice but to evolve the designs based on feedback from real-life field tests, has been instructive.

RM4L has worked with more than 20 organisations from across the industry, including technical specialists involved in developing the new technologies, manufacturers, supply chain partners, engineering firms, national construction companies and government agencies.

In addition, the potential scale of manufacture of self-healing systems for construction challenged us to design new equipment capable of tonnes per hour, rather than kilos per hour, which was a huge step up from our lab and pilot devices.

My contribution as an advisor on the IAB was to highlight the potential costs and complexities of some of the new technologies, from an industrial, rather than academic perspective.

Based on the success of RM4L, Micropore has also become involved in the European SMARTINCS programme, and one of our employees is doing a part-time PhD with Cambridge: our close involvement with the development of these technologies continues.

Government-owned company managing the UK's road network: National Highways

Chrysoula Litina
Principal Research Engineer, National Highways

Advanced materials are an area of increasing importance for National Highways. We were involved in RM4L's predecessor, M4L, the leading programme for self-healing materials in the construction and infrastructure sector. We wanted, therefore, to remain involved in RM4L in order to understand where the latest science is heading. For National Highways, the principal attraction of self-healing materials is their durability and longevity. Assets that require less maintenance cost less to run. They are safer because we do not need to put people in harm's way to repair them. They are better for road-users because they would reduce the number of road closures, creating more capacity on the network. And they are better for the environment, as fewer repairs mean we use less material and less energy.

Our role in RM4L was to provide strategic input and to help the research team understand the operational constraints of construction and maintenance and how those constraints would affect the technical specifications of the technologies.

As RM4L draws to a close, we have ongoing projects with both Cambridge and Cardiff. Some of the core RM4L approaches and technologies will be central to the new Digital Roads of the Future programme with Cambridge in which National Highways is a partner.

Self-healing, self-sensing materials are a good idea, one that continues to generate considerable interest and excitement across the organisation. RM4L has taken what was a futuristic idea and brought it to a high level of technology readiness. It is now up to us as a sector to take advantage of it.

Outreach and advocacy

A key part of the RM4L programme was communicating about our work – and about the value of STEM research more broadly – to different audiences, in order to raise awareness, build relationships and advocate for change.

Our early success in gaining media and industry attention opened further doors and meant that we were invited to talk about our work to a wide range of audiences including policymakers, industry executives, the wider research community and the general public.

These opportunities included radio interviews, television appearances, participation in exhibitions and on industry panels, engagement with industry bodies and giving keynote lectures. Through these various platforms, we were able to explain how the RM4L programme has the potential to make a difference to all our lives, position the UK as a world-leader in smart construction materials and reiterate the importance of STEM education and career paths – particularly for girls and women.

Highlights include:

Engagement with industry and policymakers

RM4L was chosen by EPSRC to be one of the exhibitors at a showcase event at the Royal Society, London in 2018. The event was aimed at industry, government departments and researchers, and featured a research exhibition and panel discussions.

To mark its 200th anniversary in 2018, ICE published a list of the 200 projects that have shaped the civil engineering world, including RM4L.

Kevin Paine was invited to join the Royal Society's Animate Materials Working Group which published a report in 2021.

The RIBA Journal, read by more than 25,000 architects in the UK, published an article titled, 'Concrete that repairs its own cracks is tantalisingly close'.

Work on bacteria-based self-healing was showcased at Futurebuild 2020 in London, a trade show focused on innovation in the built environment which attracted more than 20,000 visitors.

RM4L participated in the American Concrete Institute's non-stop 24-hours of concrete knowledge highlighting 'innovation' in concrete around the world.

Abir Al-Tabbaa was interviewed about self-healing materials in 2021 by World Economic Forum (WEF) following on from a talk she gave in 2016 on self-healing concrete for low-carbon infrastructure. This was part of a programme celebrating the tenth anniversary of WEF's annual reports on the ten most important emerging technologies.

Reaching a general audience

In 2018 the BBC featured RM4L's Cambridge lab work on microcapsules and vascular networks and the commercial deployment of self-healing and 'clinkerless' cement concrete blocks on Look East, BBC Breakfast Show and BBC World News, viewed by 60 million people.

The Oxford University Museum of Natural History showcased the Bath team's work on bacteria as part of its 'Bacterial World' exhibition in 2018.

In 2019 an animated YouTube video was produced to explain RM4L to children and families. It has had more than 1,200 views.

In 2020 RM4L participated in a Cardiff 'Museum After Dark' event, bringing the work to life through talks and demonstrations to an audience of schoolchildren and their parents.

RIGHT
RM4L team at the 7th International Conference on Self-Healing Materials, Yokohama, Japan, 2019

64
journal articles in 37 scientific journals

38
conferences in 16 countries

6
industry exhibitions

16
magazine articles and interviews

86
conference papers

25
keynote and guest lectures

5
radio and television features

1
book and 3 book chapters

4
symposia

4
school and museum events

9
awards

33
seminars and workshops

Building skills and capabilities

Professional development for early-career researchers

Developing the skills of early-career researchers was a key objective of the RM4L programme. The programme was awarded Creativity@home funding by UKRI to enhance their research capabilities and provide new opportunities for learning and innovation.

The researchers also benefited from work experience in industry. Throughout the programme, they were regularly seconded to industry partners where they could see – and participate in – 'real-world' technology transfer.

This exceptionally high level of industry engagement has resulted in around half of RM4L's postdoctoral researchers going on to work in industry in roles such as senior engineer or senior R&D manager.

Building the team

The RM4L programme launched with a two-day residential MAD (Matrix of Applications) workshop, designed to foster team-working within and across the RM4L universities and with our industrial partners. As well as building strong collaborative relationships, the workshop helped both industry and academic participants understand each other's perspectives and expectations.

Developing research skills: webinars

In 2020, RM4L ran a series of 10 skills-building webinars on a wide range of topics. The first two were for RM4L team members only but the remainder were open to researchers worldwide. The first covered intellectual property, how to protect it and how to exploit it and the second, run by industrial partner, Costain, looked at life-cycle assessment, explaining what sustainability means to industry and how to integrate the principles into our research.

Topics covered in the open seminars included scientific writing, how to get your work published, careers for women in engineering and using research tools effectively.

The open webinars were promoted widely through social media and attracted speakers and attendees from all over the world.

Developing communication skills: media training

In an intensive two-day residential media training course, facilitated by a BBC journalist, the RM4L research team and colleagues from the partner universities learnt how to talk about their research to the media and to write about it in news releases. The team also had the opportunity to experience a mock TV interview.

LEFT
Professor Susanne Gebhard being interviewed about RM4L.
Credit: University of Bath

> **"Developing the skills of early-career researchers was a key objective of the RM4L programme."**

International collaboration

Addressing the problems with concrete and other cement-based problems is a global challenge, requiring urgent global action. Taking a leadership role in developing international research networks and a strong cohort of PhDs and postdoctoral researchers was an important part of the RM4L programme. It has done this through active participation in international organisations and initiatives, designed to promote research and build capabilities in this field.

SARCOS: Self-healing As prevention Repair of Concrete Structures

SARCOS was a European initiative which ran between 2016 and 2020 with the aim of advancing research into self-healing concrete. It was funded by the European Cooperation in Science and Technology (COST), an organisation which creates networks of collaborations to drive scientific and technological breakthroughs.

Comprising institutions from the UK and 21 European countries, the programme had three working groups, one led by the University of Cardiff. RM4L Research Directors from Cambridge and Cardiff sat on the SARCOS management committee.

The programme created a wide range of opportunities for young researchers working on self-healing concrete to connect with each other and to develop their knowledge and expertise, through meetings and workshops held at participating universities, annual training schools and 'Short Term Scientific Missions'. The RM4L team hosted five of these missions, three at Cardiff and one each at Bath and Cambridge.

The activities resulted in three state-of-the-art journal articles, one from each of the work packages. In addition the team carried out an inter-laboratory study to evaluate test methods for self-healing concrete with different healing systems.

RILEM TC 253-MCI: Microorganism-cementitious materials interactions

Between 2014 and 2019, RILEM (The International Union of Laboratories and Experts in Construction Materials, Systems and Structures) created a Technical Committee to share knowledge on microorganisms-cementitious materials interactions. This was led by Professor Alexandra Bertron of INSA Toulouse, with RM4L Research Directors Bob Lark and Kevin Paine both members.

One of its four topic focuses was bacteria-based self-healing cementitious materials. The Bath team were part of round robin testing to evaluate the experiment methods for assessing the sealing efficiency of bacteria-based self-healing concrete, together with Delft University of Technology, Ghent University, Northumbria University and the University of Paris-Est. They also co-authored the chapter on, 'Bacteria-based protective systems for cementitious materials – self-healing concrete and concrete repair' for the RILEM state-of-the-art report on microorganisms-cementitious materials interactions.

SMARTINCS: Self-healing, Multifunctional Advanced Repair Technologies in Cementitious Systems

Set up with funding from the European Union's Horizon 2020 research and innovation programme, SMARTINCS is a European consortium of research institutions and industry partners from across the value chain, all with a shared ambition to introduce self-sensing and self-healing technologies into the construction market. RM4L universities Cardiff and Cambridge and industry partner Micropore are all members of the consortium.

It aims to make progress by providing training and networking opportunities to 15 early-career researchers, giving them the knowledge and skills to help accelerate the implementation of new approaches to the concept and design of concrete structures. Of the 15 researchers selected by SMARTINCS, four are involved in the RM4L programme.

In November 2021, the University of Cambridge hosted the second SMARTINCS Training School. It was the first opportunity for the 15 researchers to meet in person since the start of the project. The week-long training school included a range of presentations focusing on infrastructure repair as well as hands-on practical work. Presentations were given by a number of academic and industry partners, including National Highways. Talks were also given on encapsulation techniques together with a laboratory demonstration session provided by Micropore.

Governance

To make sure that RM4L was addressing industry needs and remained connected with developments taking place across the wider research community, RM4L established two advisory boards which met at six-monthly intervals throughout the programme. The boards provided expert advice and guidance, ensuring that the programme achieved its research and impact goals as well as helping the RM4L team engage with the wider academic, industry and policy audiences.

Industrial Advisory Board (IAB)

The IAB was established to provide industrial leadership and guidance to ensure the researchers were responding to real industrial needs.

Throughout the programme, the IAB guided the researchers on which industry problems are the most pressing and which technologies are the most promising. Its members have worked closely with the researchers to identify practical applications for the emerging techniques and have advised throughout on what barriers need to be overcome if they are to be widely adopted.

"There are many challenges and technical applications these technologies could address, but what the IAB has done very well is to prioritise them. Its input has helped the researchers focus on how the technologies could be used in different industry applications and understand their potential benefits."

Tim Embley
Director of Innovation, Costain and IAB Chair

"It is certain that some of these technologies will be trialled by HS2 in order to meet the resilience and robustness required for the operation of our service. The next challenge is taking those trials and getting them to a point where they go from something novel to something which is proven. I think we can already see some of those technologies identified as front-running candidates. Some of the most exciting are at a lower TRL because they have very wide potential applications."

Don Wimpenny
Lead Materials Specialist, HS2

"To apply all the effort that has gone into understanding and progressing these technologies we need to help the rest of the sector and supply chain partners understand the economic benefits."

Chrysoula Litina
Principal Research Engineer, Highways England

"This is a fantastic project. The next hurdle is how can we get these products included in design and product standards that would enable me then to include them in my concrete and get the benefit."

Richard Kershaw
National Technical Manager, CEMEX

Industrial Advisory Board (IAB)

Chair

Tim Embley
Director of Innovation, Costain

Board members

Tim Beeson
Senior Materials Engineer, Balfour Beatty

Dave Gullick
Operations Director, Sweco

Jason Hibbert
Head of Structures, Welsh Government / Representative of Bridge Owners Forum

Richard Kershaw
National Technical Manager, CEMEX

Chrysoula Litina
Principal Research Engineer, Highways England

Dr Paul Lyons
Managing Director, LUSAS

Dr Richard Morgan
Head of Asset Management & Standards, Welsh Government

David Palmer
Business Development Manager, Micropore Technologies

Andy Powell
Innovation Manager (Construction), Environment Agency

Dr Ricardo Teixeira
Associate, Mott MacDonald

Don Wimpenny
Lead Materials Specialist, HS2

External Scientific Board (ESB)

The ESB, led by Professor Barry Clarke, comprising both independent academics and industrialists, provided independent advice to the RM4L programme. Its role was to provide wider research context and to consider both the direction of the research and how it was conducted.

Chair

Professor Barry Clarke
Professor of Geotechnical Engineering, University of Leeds (UK)

Board members

Professor Gordon Airey
Professor of Pavement Engineering Materials, University of Nottingham (UK)

Professor Nele De Belie
Professor in Durability of Cement Bound Materials, Ghent University (BE)

Professor Ian Bond
Professor of Aerospace Materials, University of Bristol (UK)

Dr Edurne Erkizia
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Professor Chris Pearce
Professor of Computational Mechanics, University of Glasgow (UK)

Professor Peter Robery
Professor of Forensic Engineering, University of Birmingham (UK)

ABOVE
Commercial deployment of microcapsule-based self-healing concrete. Credit: University of Cambridge

Looking ahead

The RM4L grant programme has enabled us to make significant advances in our understanding of self-diagnosing and self-healing materials, technologies with a vital role to play in maintaining the world's buildings and infrastructure and in reducing the environmental impact of the construction industry.

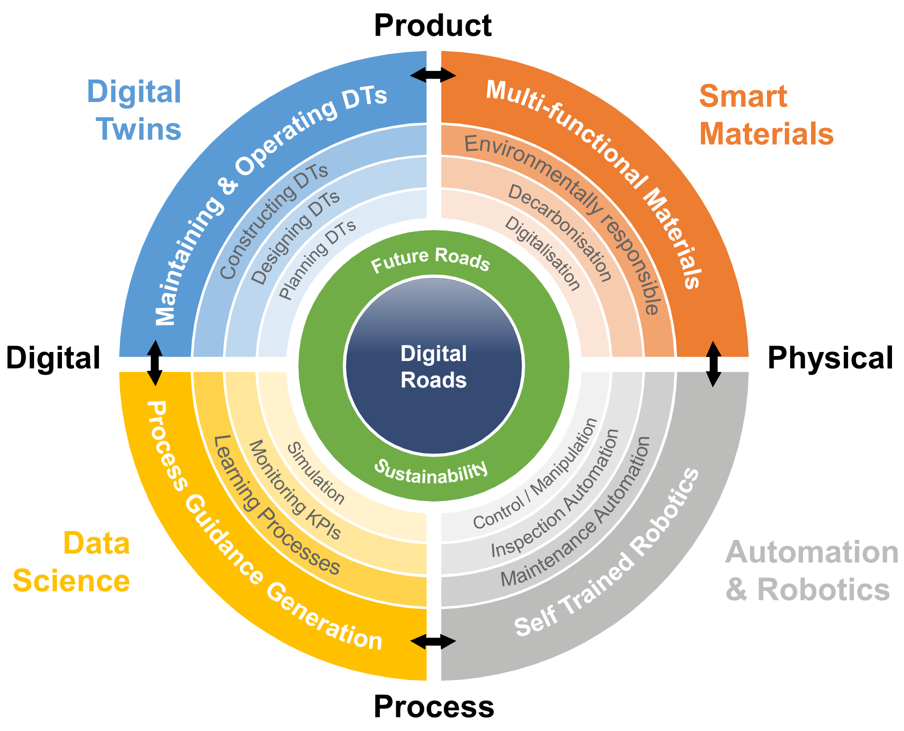
Through close collaboration with industry and by running trials in real-world settings, a number of technologies emerging from this research are showing real promise.

Digital Roads of the Future

More research and further trials are now required to take these technologies forward. For the Cambridge team, its work on smart, self-healing materials is now part of two major new research programmes: the Digital Roads Prosperity Partnership, an £8.6 million EPSRC-funded project with industry partners Costain and National Highways. The second is the Future Roads Fellowship, which has been awarded £5.9 million by the European Commission COFUND programme. Together these two research programmes combine to form the Digital Roads of the Future initiative which has an ambitious goal of transforming our road networks, to make them both safer and greener.

The scope of the initiative is broad. Its aim is to make roads and pavements smarter and more sustainable, to digitalise the network (using sensors and digital twins) to make it more efficient and safer for road-users and to build resilient roads that can monitor their own performance over time. The research undertaken for RM4L by the Cambridge team will be at the heart of the Digital Roads of the Future's 'Smart Materials' theme which seeks to decarbonise our roads and pavements, allow them to monitor and manage themselves and to design them in a way that is environmentally responsible and that anticipates and mitigates the impact of climate change.

In addition, the RM4L team sees a number of future directions for its research.



Sustainable manufacturing

A priority for all the university partners is how to produce their novel technologies at scale using processes and materials – including recycled materials – which reduce their environmental impact and how to adapt them for use in low-carbon concrete.

The focus to date has been on applying their techniques to the types of concrete that are in widespread use today. However, concrete will change. More work needs to be done to understand how the techniques will work in the structures of the future and to explore new ways to help countries achieve their net zero carbon ambitions, perhaps by capturing carbon as part of the production process.

Maintaining heritage buildings

As well as developing technologies that can be integrated into new structures, we also need to consider whether they can be harnessed to repair and maintain existing buildings. New research is looking at how vascular networks might be used in heritage structures and some of the challenges these structures present. How, for example, can we deploy the technologies without causing damage and how can we monitor their performance over time?

Creating 'living' concrete

For the team working on bacteria-based self-healing, the immediate challenge is to produce spores at a sufficiently large scale for commercial implementation and to test the technique in-situ over the long term.

The team is also starting to investigate other applications for its biomineralisation techniques, such as using the biofilms formed by the bacteria as glues to improve the properties of construction materials, as carried out in collaboration with the company Adaptavate. It is also exploring, 'Engineered Living Materials' where the bacteria, by producing calcite, are effectively able to grow an artificial limestone around sand, creating a material which could potentially retain some living biological properties. These could include self-healing but also, perhaps, the ability to respond to their environment by, for example, developing waterproofing in wet conditions.

This research area is attracting widespread interest and is one that the University of Bath is well placed to pursue, having already solved the problem of how to genetically engineer calcite-producing bacteria.

> **"The RM4L programme grant has developed several transformative technologies that will enable buildings and infrastructure to diagnose and repair themselves."**

The RM4L programme grant has developed several transformative technologies that will enable buildings and infrastructure to diagnose and repair themselves. The research team has worked with industry to bring them close to commercialisation, although some barriers to adoption remain. More research is needed to overcome those barriers, to find new opportunities to apply the RM4L technologies and to continue reimagining what we build and how we build it.

LEFT
Vision of Digital Roads of the Future initiative. Credit: University of Cambridge

ABOVE
Dr Cristina Tuinea-Bobe installing a mould tool in a Fanuc injection moulding machine.
Credit: University of Bradford

Acknowledgements

With thanks to the following people and organisations who also contributed to RM4L:

Additional researchers

Cardiff University

- Carlos Azua-Gonzalez
- Amrit Bains
- Dr Pedro Bonilla-Villalba
- Gwilym Evans
- Thomas Moore
- Salah Salman
- Yu Wang
- Dr Ioanna Papanikolaou
- Richard Parsons
- Zixuan Tang
- Regana Vasanthanayagam
- Xueying Wang
- Briony Whitfield
- Zijun Xie
- Qiaofeng Zheng

University of Cambridge

- Benyi Cao
- Jingtao Chen
- Qingkai Chen
- Ruth Faherty
- Dr Heba Hamad
- Aleks Janowska
- Yu Jiang
- Hana Khan
- Zijing Li
- Wenting Mao
- Ana-Maria Marcu

University of Bath

- Jasdeep Ghataora
- Dr Timothy Hoffmann
- Lorena Skevi
- Dr Linzhen Tan
- Jiacheng Zhang

Industry partners

- Arup
- Atkins
- Balfour Beatty
- BRE
- CEMEX
- CH2M Hill
- Costain
- Environment Agency
- Fosroc
- Graphitene
- Griffiths
- HS2
- Isle Utilities
- Jacobs
- Lambson
- LUSAS
- Micropore Technologies
- Mott MacDonald
- National Highways
- SABIC
- Sweco
- Tarmac
- Technalia
- Travis Perkins

The RM4L team acknowledges the financial contribution from the UKRI Engineering and Physical Sciences Research Council for the RM4L programme grant (grant number EP/P02081X/1).

Authors: Abir Al-Tabbaa, Diane Gardner, Kevin Paine and John Sweeney with contributions from the RM4L team.

Editorial: Sarah Fell

Design: CantellDay

September 2022

Site trial of self-healing concrete carried out in 2015 as part of M4L.
Credit: University of Cardiff

RESILIENT MATERIALS 4 LIFE

Cardiff University / Prifysgol Caerdydd

University of Bath

University of Bradford – Making Knowledge Work

University of Cambridge

UKRI – Engineering and Physical Sciences Research Council