RESILIENT MATERIALS 4 LIFE - RM4L

VISION AND AMBITION

The vision of RM4L is that by **2022** we will have achieved **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** (Fig. 1). This innovative research into smart materials 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. It will deliver our **2050 ambition**, as set out in M4L, of **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**.

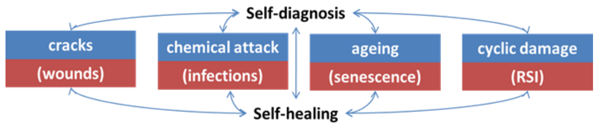

Fig. 1. RM4L 2022 Vision

ADDED VALUE AND SYNERGY

This research project has a clear vision to transform the Nation's built environment by facilitating the delivery of new and existing infrastructure that is sustainable and resilient, using low carbon, adaptable and sustainable construction materials. The potential impact of these self-healing, self-diagnosing and self-immunising construction materials on the UK economy is enormous. Indeed, currently, 40% of all construction spending is on repair and maintenance. Improving our current and future infrastructure (energy, transport, water, waste and resources) is a national priority and the Government has recently invested £138 million in the UK Collaboration for Research in Infrastructure and Cities (UKCRIC). This research will contribute to the impact of this investment. Our vision for construction materials that are more resilient, intelligent, environmentally friendly and less costly than currently available materials will facilitate the UK's transition into a low carbon economy and will engender a step-change in the value placed on infrastructure materials by providing a much higher level of confidence in the reliability of their performance. It will bring significant economic (reduction in construction and maintenance costs) and societal (reduction in disruptions, delays and emissions) impacts. Industry and those responsible for the provision, management and maintenance of the world's built environment infrastructure will be the main beneficiaries and we will realise our vision by addressing applications informed by practice. Together with industry and by engaging with complementary initiatives such as UKCRIC, we will develop a suite of real life demonstration projects. We will further enhance the diversity and reach of our existing UK Virtual Centre of Excellence for intelligent, self-healing construction materials and we will further exploit established relationships with the international community of SH researchers to maximise impact and thereby generate new initiatives in a wide range of related research areas. Our intention is to exploit the momentum in outreach achieved during the M4L project and advocate our work and the wider benefits of EPRSC-funded research through events targeted at the general public and private industry. We will establish the UK as the world leader in this emerging area of intelligent construction materials.

RESEARCH THEMES (RTs) AND THEIR INTER-RELATION

The ambitious programme of inter-related work is divided into four RTs. These bring together four complementary technology areas (i.e. self-diagnosing (SD); self-healing (SH); modelling and tailoring; scaling up) to address the diverse range of applications identified in Fig. 2. The technologies and science to be developed in each of them are interdependent and feed into one another. They comprise different damage and response scenarios, which in the real world are needed to work together. It is the synergy and interconnections between them and the associated cross-fertilisation that will together provide the true added value.

Each cross-cutting application will draw work from all 4 RTs, will involve all 3 lead institutions, and each will have a nominated 'champion' to ensure viable solutions are developed. There are multiple inter-relationships between the Themes, e.g. technologies from RT1 to RT4 will be tested in the RT1 field trials that bring all the technologies together; SD methods developed in RT3 will rely on the SH technologies from RT1; SH research in RT1 will be essential for the development of time-dependent SH systems (RT2); principles of SD established in RT3 will be employed in RT4; tailoring procedures for immunisation and SD processes (RT3) will employ the computational tools developed in RT1 & RT2. Overall, the methods, technologies, models and procedures considered in any one RT will inform the others. The nature of the proposed research will be highly varied and encompass, amongst other things, fundamental physico-chemical actions of healing systems,

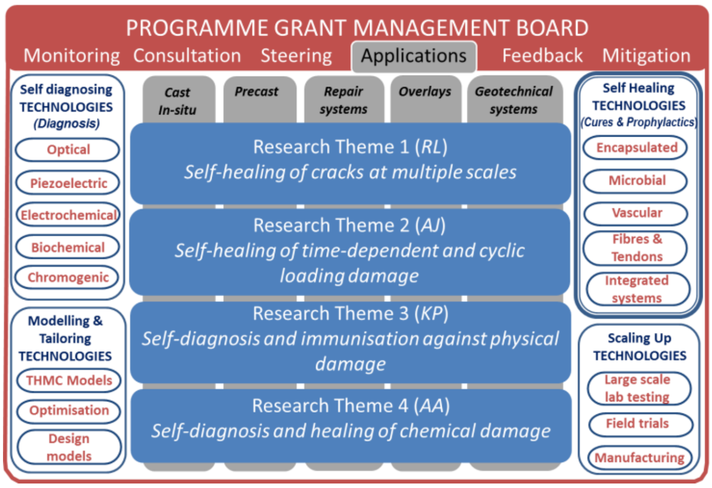

Fig. 2. Overview of work programme

For more info please visit www.RM4L.com or email to info@RM4L.com flaws in potentially viable SH systems; embryonic and high-risk ideas for SH and SD; and underpinning mathematical models and optimisation studies for combined SD/SH systems.

Research Theme 1. (RT1) *Self-healing of cracks at multiple scales.*

Building on the leading-edge research of M4L, a range of multi-scale SH technologies will be brought to fruition. This will include exciting new technologies that present a host of fundamental research challenges, e.g. the development of bacterial healing systems that can work in marine environments (halophiles) and cold conditions (psychrophiles), the use of capillary networks to supply oxygen for sub-surface healing and/or use of non-aerobic bacterial healing systems, and use of synthetic biology techniques to optimise bacterial growth and healing ability in mixed environments. Further examples include very high performance shape-memory polymer (SMP) tendons that can eliminate conventional reinforcement; pressurised mini-networks containing innovative prophylactic agents; and the refinement and optimisation of the microcapsule design to achieve enhanced versatility for specific applications. This RT will also address the challenge that materials used in present-day construction are too generic in nature and are rarely tailored for specific applications, e.g. concrete used in different applications is essentially the same despite the fact that the operating and exposure conditions are dramatically different. The range of material solutions to be developed in this theme will provide a suite of material systems that can be tailored to specific applications. To achieve this, RT1 will undertake ground-breaking work on developing state-of-the-art numerical analysis tools, design procedures and optimisation studies. Full-scale testing and site trials will also be an essential component of this theme. Different SH systems have different operational scales, and an optimum material solution may comprise one or multiple technologies. This testing and the site trials will involve all Institutions and will explore the full range of technologies, their interactions and applicability.

Research Theme 2 (RT2). *Self-healing of time-dependent and cyclic loading damage*

Many time varying actions cause damage in cementitious systems. Some are relatively long-term and relate to the basic nature of the material (e.g. creep and shrinkage, which can lead to excessive deformations and micro-cracking), whilst others derive from short-term external actions (e.g. cyclic loading derived from traffic or earthquake loading). High-performance SMP tendons have the potential to change the stress distribution within a structural element, and thereby cause partial creep recovery. For cyclic loading, the damage-healing rate ratio becomes an increasingly important parameter and this requires more investigation. A further issue with multiple SH cycles is 'strain ratcheting'. RT2 will include: (i) developing microcapsules with rapid healing cargoes and resilient capsules that will only be triggered by damage and not by other environmental actions; and (ii) exploiting the cyclic nature of bacterial healing that follows a natural cycle (i.e. spores→germination to live cells→growth→end of growth→spores) that has yet to be proven in cementitious systems.

Research Theme 3 (RT3). *Self-diagnosis and immunisation against physical damage*

The use of SH construction materials is of great significance to structures in which conventional monitoring and repair is difficult or even dangerous, e.g. power stations, underground and underwater structures. Minimising human interaction is paramount and consequently the proposed intelligent and resilient construction materials will have more than just the capability to self-heal physical damage. They will also self-sense damage, self-diagnose the significance of the damage, and self-control a response. This would be analogous to having a central nervous system (CNS) controlled by a brain. A realisation of such a system could comprise piezoelectric devices (nerves) transmitting messages to a micro-processor (brain) that would activate an SMP grid to create a stress state in which impending micro-cracking is prevented (immunisation). In RT3 a range of exciting sensing technologies will be harnessed. These will include electrically conductive powders and nanocomposites. A research ambition of RT3 is to create sensing and immunising microcapsules, using functionalised mechano-responsive shells, which are programmed to rupture at predefined stress levels, lower the stress level in the host matrix, release the cargo prior to damage and thereby prevent, or substantially minimise, its effect.

Research Theme 4 (RT4). *Self-diagnosis and healing of chemical damage*

Structures formed from cementitious materials suffer from many chemically-based deleterious actions, such as chloride ingress, alkali aggregate reactions (AAR) and sulfate attack. This damage can manifest as weakened areas of material, oxidisation of reinforcement, loss of rebar cover, material expansion and internal micro-cracking. In some cases, damage, e.g. corrosion of prestressed tendons inside concrete, is not detected until too late. Corrosion is the largest and most costly deterioration problem in reinforced concrete, with a global budget of >$2 trillion and >£1 billion in the UK. Developing systems for SD and SH in cementitious systems prone to chemical damage is the prime challenge here. This will include radical research into a number of microcapsule-based solutions including; microcapsules with shells that chemically disintegrate; that can neutralise chloride or carbonation fronts; that can make use of recent breakthroughs in the role of graphene in the control of steel corrosion or that can release novel mineral corrosion inhibitors which encapsulate the expansive corrosion products. Combined capsule systems that SD and SH both physical (from RT1 & RT3) and chemical damage will be investigated and we will attempt to exploit the property of certain bacteria, such as the alkaliphile *Bacillus pseudofirmus*, which, in the vicinity of reinforcement, could provide a response to carbonation by favourably changing the local pH level. We will also develop a combined SD-SH vascular network system containing pozzolanic agents that counteract sulfate attack and couple this system to electro-chemical sensors.