BIOMIMETIC MULTI-SCALE DAMAGE IMMUNITY FOR CONSTRUCTION MATERIALS: M4L PROJECT OVERVIEW

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ABSTRACT

This paper presents a vision of a sustainable and resilient built environment that is comprised of materials and structures that continually monitor, regulate, adapt and repair themselves without the need for external intervention. In this way, these self-healing materials and intelligent structures will significantly enhance durability and serviceability, improve safety and reduce maintenance costs. The conglomerate materials that form the basis of the majority of such construction materials (concrete, grouts, mortars, hydraulically bound materials, grouted soils etc), are extremely complex multiphase composites with multi-scale internal structures that exhibit a hierarchy of multi-dimensional, time-dependent damage mechanisms. For example, in cementitious composites nano-scale damage occurs during hydration and the strength development phase, while medium-term damage due to chemical attack also leads to the formation of defects in its structure. Other short-term factors can also produce dislocations at the nano-scale. In time, this nano-damage grows to form micro-cracks which eventually coalesce to form networks of meso-cracks which in turn lead to debonding between the paste and aggregate particles, followed by a discrete number of visible macro-cracks which so often lead to corrosion of the steel reinforcement. Hence, it is evident that to truly achieve a self-healing cementitious composite, a system is needed that can act at both the different time and length scales at which the damage can form. This paper presents a newly funded research project, M4L: Materials for life, that is addressing this complex problem by taking advantage of innovations in allied scientific disciplines to pave the way for the development of a new generation of versatile and robust construction materials.

1. INTRODUCTION

The resilience of building and civil engineering structures is typically associated with the design of individual elements such that they have sufficient capacity or potential to react in an appropriate manner to adverse events. Traditionally this has been achieved by using 'robust' design procedures that focus on defining safety factors for individual adverse events and providing redundancy. As such, construction materials are designed to meet a prescribed specification; material degradation is viewed as inevitable and mitigation necessitates expensive maintenance regimes. More recently, based on a better understanding of microbiological systems, materials that have the ability to adapt and respond to their environment have been developed [1]. This fundamental change facilitates the creation of a wide range of 'smart' materials and intelligent structures, including both autogenous and autonomic self-healing materials and adaptable, self-sensing and self-repairing structures. Such materials can transform our infrastructure by embedding resilience in the materials and components of these structures so that rather than being defined by individual events, they can evolve over their lifespan.

2. SCOPE AND AIMS

Conglomerate materials, which form the basis of the majority of construction materials (concrete, grouts, mortars, hydraulically bound materials, grouted soils etc), are extremely complex multiphase composites with multi-scale internal structures that exhibit a hierarchy of multi-dimensional, time-dependent damage mechanisms. In cementitious composites *nano-scale damage* occurs at the level of the calcium silicate hydrate (C-S-H) gel during hydration and the strength development phase, while medium-term damage due to chemical attack can also lead to the formation of defects and dislocations in its layered structure. Other short-term factors such as residual stresses that arise during curing and compaction or longer-term physical actions, like repeated cycles of freezing and thawing and fatigue loading, can also produce dislocations between the C-S-H globule-like nanoparticles. In time, all the nano-cracks grow to form dislocations between the C-S-H matrix and other crystals like portlandite within the cement paste (*micro-scale damage*). These micro-cracks eventually coalesce to form networks of meso-cracks. These meso-scale cracks lead to debonding between the aggregate particle and the paste (*meso-scale damage*). Finally the meso-scale network grows to become a discrete number of visible macro-cracks *(macro-scale damage)* which can permit processes leading to corrosion of steel reinforcement. Hence, it is evident that to truly achieve a self-healing cementitious composite a system is needed that can act at both the different time and length scales at which the damage can form.

Similarly, when damaged, higher organisms, including man, use intrinsic immune systems and wound responses to provide a multi-scale response, from a chemical and cellular level through to the macro-scale at which any lesion is bound together and sealed to facilitate the healing process. Inspired by this, the intention is to create construction materials with an inbuilt “immune” system that is responsive to the condition of the material and the onset of damage. This will operate at the nano/micro-scale using micro-encapsulation strategies, at the micro/meso-scale through bacterial healing and at the meso/macro-scale, with fibres, shrinkable polymers and vascular networks (fluid filled micro-scale channels) providing mechanisms to enhance and control the overall physical response. One of the main challenges will be to ensure that, as in the biological systems, these multi-scale healing mechanisms are an appropriate response to the type of damage, are complementary and work synergistically.

3. MATERIALS AND METHODS

While microencapsulation for self-healing materials was pioneered over a decade ago for polymer composites, the development of simple, efficient, cost-effective, environmentally-benign and scalable synthesis techniques without compromising functionality and encapsulation efficiency remains a major challenge. Microencapsulated reactive agents have been considered for applications in building construction materials (fireproofing, antimicrobial protection, temperature control, freeze-thaw resistance) [2] but their application to self-healing is relatively new [3]. Recently, scientists at Cambridge have developed a simple and scalable one-step process, by combining supramolecular host-guest chemistry and a microfluidic droplet platform technology (Figure 1), for the synthesis of highly uniform microcapsules with high cargo loading efficiency, long shelf-life and easily customizable functionality [4]. Cargos can be chemical, biological, liquid or solid and the capsule shell composition and chemistry can be easily manipulated to suit different stimuli and trigger mechanisms. For example, its porosity, stiffness and strength can be designed to facilitate permanent storage (for crack stress trigger) or controlled on-demand release (for diffusion related sealing) of the cargo; it can be made to disintegrate under electrochemical redox reactions (e.g. corrosion); it can be made to expand/contract in a controlled manner and it can contain separate cargos e.g. catalysts.

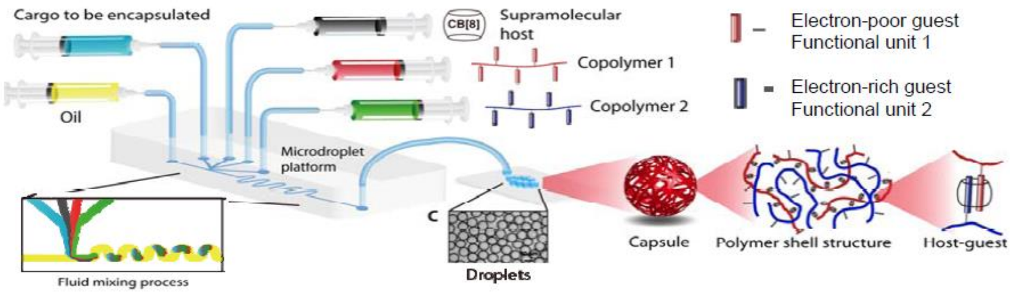

Figure 1: A schematic of the Cambridge microencapsulation synthesis technique [4].

At the meso-scale the use of alkali-resistant spore-forming bacteria from the genus *Bacillus* to heal cementitious materials, ornamental stones and degraded limestone has been the subject of active research since 2000. Bacterial healing utilises the metabolic activity of bacteria and biomineral precursors embedded within the material to form an inorganic material, usually calcium carbonate ($CaCO_3$) in the form of calcite. It focuses on two major areas – sealing (reducing permeability) of exposed surfaces and cracks to prevent ingress of deleterious chemical species, and healing (strength recovery) of macroscopic and microscopic cracks, re-establishing the ability of the cracked zone to carry load. Bacteria have the capacity to bind Ca ions thanks to charge effects and associated extracellular polymers. Calcite has been commonly derived indirectly from the enzymatic hydrolysis of urea, however this reaction yields ammonia, which is environmentally damaging and urea has limited long-term stability in alkaline conglomerates. Therefore it has been most usefully applied as external treatment and not as a self-healing agent [5]. In light of this the potential of multi-component healing agents that do not yield harmful products when broken down are being investigated [6] with precursors such as calcium lactate, which when driven by metabolic absorption produces $CaCO_3$, CO_2 and water, all of which are compatible with cementitious hydrates. However, whilst the potential for bacterial healing has been demonstrated in idealised laboratory conditions the extent of the healing/sealing that is possible and the long-term viability of the *Bacillus* spores is still to be determined.

At the macro-scale construction research has focussed on either developing systems that can heal themselves autonomically (e.g. via glues or resins) or are able to enhance the autogenic healing capacity of many cementitious compounds. A novel technique that is being developed at Cardiff, is to embed shape memory plastic (SMP) tendons into the cementitious matrix with the aim of creating a material system which can either close cracks to a degree whereby they can be healed by one of the in-built healing systems discussed above (Variant I) or prevent them from occurring (Variants II and III) as shown in Figure 2. SMPs often develop relatively low “recovery” or “shrinkage” stresses when undergoing the shape transition under restrained conditions. However, materials in which the shrinkage stress level is sufficient to provide this inbuilt mechanism for closing cracks have now been identified [7] and the opportunity exists for further development to include manufacture from recycled plastics.

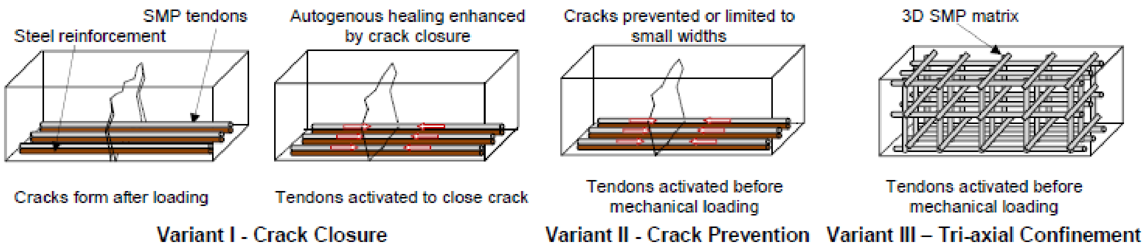

Figure 2: Schematic illustration of concept for composite material system

4. FURTHER STUDY

Inspired by nature, the intention of this project is to develop an interdisciplinary, multi-scale system utilising a range of technologies to promote and enable self-healing of construction materials over various timescales. In particular there is a focus on conglomerate materials such as concrete, grouts, mortars, hydraulically bound materials and grouted soil systems. A range of damage scenarios and structural and geotechnical engineering applications are being addressed including, at the micro-scale, microbiological and chemical healing, focussing on both the methods of delivery (e.g. microencapsulation) and the operation of these systems. At the meso-scale the overall impact and distribution of these microscopic systems are being considered and optimised. At the macro-scale, large-scale healing systems, such as shrinkable polymers and vascular networks are being developed and implemented. Combinations of these systems in different materials and scenarios to give a whole-material response to damage at a range of spatial and temporal scales are being exploited and field-scale tests to address relevant aspects of scale-up, cost, commercialisation as well as full-scale damage scenarios are going to be performed.

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