The Requirements for Autonomic Microbiologically-Induced Calcite-Precipitation in Concrete

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ABSTRACT

This paper addresses the complex problem of using microbiologically-induced calcite-precipitation as a means of autonomic self-healing of concrete and describes the requirements for the encapsulated bacteria, precursors and nutrients. The paper discusses the need to use copious spore-forming alkaliphilic bacteria that germinate relatively quickly and considers the kinetics of microbiologically-induced calcite-precipitation. Issues relating to pH and temperature are also discussed. The paper also considers the compatibility of the nutrients and organic precursors with concrete. It is concluded that whilst the encapsulation of bacteria, nutrients and organic precursors that lead to microbiologically-induced calcite-precipitation is readily achievable, optimisation of the process requires further biological and engineering research. Some key areas of further fundamental research are highlighted.

1. INTRODUCTION

Concrete can deteriorate in some aggressive environments and approximately £35 billion/year is spent in the UK on repair and maintenance of concrete structures. In order to provide a solution to the problem the University of Bath are collaborating with Cardiff University and the University of Cambridge in the EPSRC Materials for Life (M4L) project that is delivering a multi-scale self-healing system for concrete that will lead to significant reductions in repair and maintenance [1]. The work at Bath is developing microbiologically-induced calcite-precipitation (MICP) using the metabolic pathway as conceived at TU Delft [2]. The healing requires bacteria to act as a catalyst for the conversion of an organic calcium salt (precursor) to calcite under favourable conditions, including the presence of water, oxygen and nutrients.

However, this form of MICP is complex as it is necessary to encapsulate all the ingredients (bacteria, nutrients and organic precursors) within the concrete during the mixing stage and maintain them within an inert condition until such time that a crack appears and healing is required. Consequently it is necessary that any ingredient used does not affect the setting and hardening of the concrete. Once a crack appears the ingredients must become active and form calcite rapidly within the crack without adversely affecting undamaged concrete and steel reinforcement. This restricts the choice of ingredients that may be used.

2. BACTERIA

A number of bacteria for providing MICP have been used in previous research, with a key criterion that the bacteria should be able to thrive in the dry and alkaline environment present in hardened concrete. Therefore, most research has focused on the use of spore-forming alkaliphilic bacteria in particular those of the *bacillus* genii. Research at the University of Bath has used commercially available *Bacillus cohnii 6307*, *B. pseudofirmus 8715*, *and B. halodurans 497, as* alkaliphilic strains known to be copious calcite producers in order to compare efficiency of precipitation, time of precipitation, and the effects of pH and temperature.

A self-healing mechanism should only become active when required and consequently the bacteria are initially added to concrete as endospores; a state in which they are able to withstand mechanical and chemical stresses, nutrient depletion, desiccation and extreme temperatures. However once these spores are exposed to a suitable environment the endospores return to the vegetative state (germination). These conditions are intended to exist once a crack occurs and water and oxygen come into contact with the endospore. From a practical point of view it is important that suitable endospores can be obtained quickly and relatively cheaply. Research at the University of Bath has shown that complete sporulation of all three bacteria strains mentioned above can be achieved in less than 24 hours in the presence of suitable sporulation aids.

In normal circumstances, the pH of the concrete at the moment a crack will occur will be greater than 7. However, generally speaking alkaliphilic bacteria are those that grow very well at pH values above 9, often between 10 and 12, but cannot grow or grow only slowly at near-neutral pH [3]. Therefore should the concrete be sufficiently well carbonated by the time it cracks then self-healing will be slow or non-existent. Likewise should cracks form at early-age, before carbonation has occurred, there is a possibility that the pH of concrete will be too high for healing to occur (Figure 1). Consequently there may be a need in some applications to embed the bacteria with a buffer solution to maintain the pH at a viable alkalinity. As far as the authors are aware the relationship between optimum conditions for growth of bacteria and the likely pH of the concrete at any time in its life have not been studied.

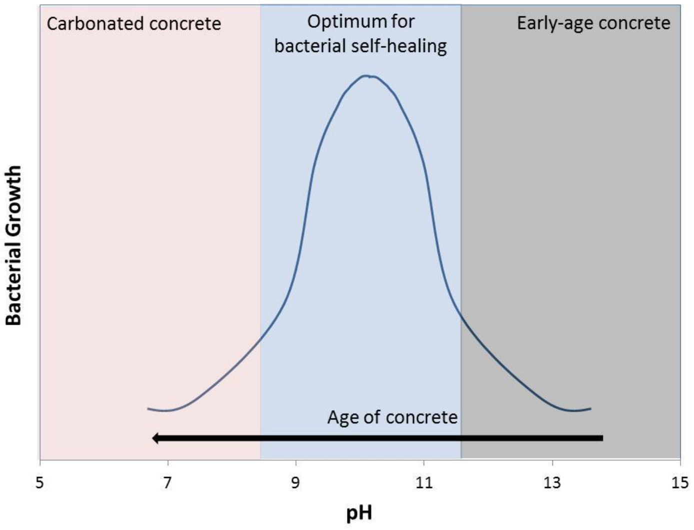

Figure 1: Relationship between pH of concrete and optimum growth of alkaliphiles

Furthermore in relation to their ability to be used in concrete exposed to different conditions the choice of bacteria used may depend on their ability to cope with hot and cold temperatures, and salt and fresh water. Many of these attributes have not yet been considered. Research at Bath has shown that *B. cohnii*, *B. pseudofirmus and B. halodurans* grow well at temperatures between 25 and 35°C. However, this does not necessarily correlate with their ability to optimally biodeposit calcite.

3. PRECURSORS

Precursors are required in self-healing concrete for conversion to the healing compound. To date most research into healing of concrete via bacteria action has concentrated on the formation of calcium compounds, normally calcite as the healing agent and consequently researchers have used calcium based compounds as precursors.

Jonkers et al [2] have considered a range of organic calcium precursors and suggested calcium lactate as a prime candidate as it does not cause a loss of strength when added to concrete. However, since the current state-of-the-art is that the calcium precursor should be encapsulated within the concrete this has opened up the possibility for a much wider range of precursors such as calcium acetate and calcium nitrate. Although widely used *in vitro*, it is important that calcium chloride should not be used as the precursor in self-healing concrete due to the contribution of Cl^- ions to passivation of steel in hardened reinforced concrete.

4. NUTRIENTS

The additions added to the cargoes to facilitate precipitation of a healing compound need to play a number of roles, but most importantly: (i) provide a source of nutrients (growth medium) for the bacterial cells and (ii) aid the germination of the endospores.

To study MICP *in vitro* biologists use standard growth mediums, for example, B4 medium or a Luria-Bertani broth, modified by the addition of calcium precursors. However, systems used in concrete have tended to use fewer ingredients with probable consequences for the growth of the bacteria and consequently the degree of healing. Work at Bath is attempting to optimise the nutrients required. However, whilst these essential components need to be encapsulated within the concrete, there remains a concern that capsules could burst during mixing and that the release of these nutrients could affect the quality of concrete (Table 1).

Table 1: Effect of common nutrients on early-age properties of concrete

Nutrient	Reason for use	Effect on concrete
Yeast extract	Source of nitrogen	Retards setting and hardening
Glucose and dextrose	Source of carbon	Retards setting and hardening
Peptone, tryptone, trypticase etc.	Source of nitrogen	Reduces strength [2]
Tris	In buffer solutions	Increases rate of hydration [4]

Whilst pioneering work on self-healing concrete [e.g [2]] has been relatively successful in demonstrating MICP without germination aids; there are concerns relating to low germination rates and consequently low mineralizing capacity. Work at Bath has used alanine and inosine as germination triggers, in the presence of NaCl, and shown rapid germination (Figure 2). The use of these aids, preferably with an alternative Na source, should lead to a more efficient self-healing process and is under investigation.

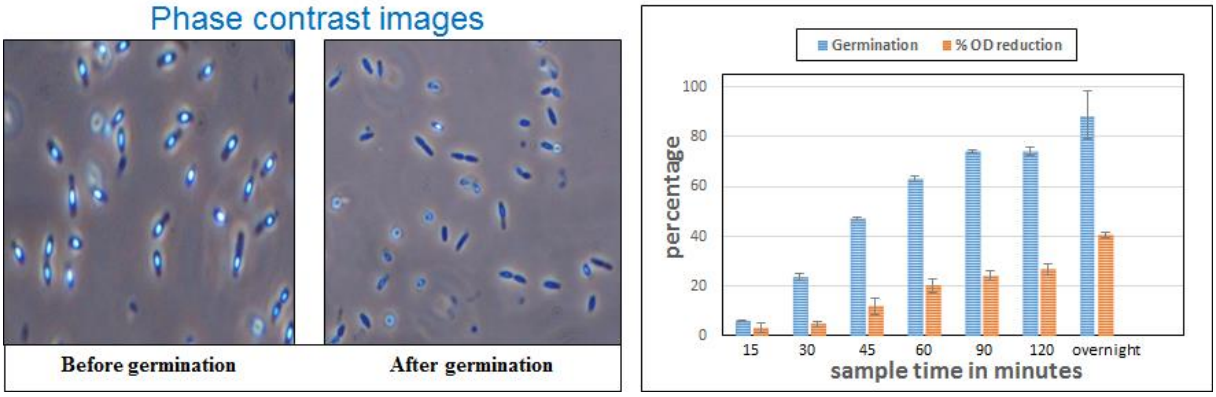

Figure 2: Spore germination kinetics of *B.pseudofirmus* at 30°C

5. CONCLUSIONS

The encapsulation of a set of ingredients that lead to MICP in the context of self-healing concrete is readily achievable. However, further biological and engineering research, such as that currently being carried out at Bath is required to ensure the appropriate selection of bacteria, precursors and other nutrients. Importantly the bacteria should grow well when concrete cracks occur, and buffer solutions should be provided where appropriate. Organic calcium precursors should not adversely affect the concrete and should preferably produce a high quantity of calcite in relation to their molecular size. An array of growth and germination aids are needed, but formulations should be carefully tailored to ensure an optimum yield of bacteria in relation to the volume of nutrients added.

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