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## **HEALCON: Self-healing concrete to create durable and sustainable concrete structures**

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### **ABSTRACT**

HEALCON is a project funded by EU-FP7 and coordinated by Prof. Nele De Belie (Ghent University). Its aim is to design smart concrete with self-healing properties to create durable and sustainable concrete structures.

In a first phase of the project, different types of healing agents and encapsulation techniques have been developed and finalized. Depending on the type of damage, another self-healing concept was envisioned in the project. While superabsorbent polymers and bacterial healing agents are suitable for healing of early age cracks in structures which require liquid tightness since they produce a non-elastic material that fills the crack, elastic polymers can be used for healing of bending cracks since they can cope with the opening and closing movement of cracks under dynamic load.

The efficiency of the different self-healing mechanisms with regard to mechanical behaviour, liquid-tightness and durability was firstly quantified at lab-scale. Besides, computer models were developed to simulate the fracturing and self-healing mechanisms in order to refine lab tests and to ultimately scale the mechanisms to an industrial level. Then, the most promising healing agents, for which the production could be easily up scaled, were incorporated in large scale elements (slabs and beams) to validate experimentally the self-healing methodologies. To characterize healing, non-destructive monitoring techniques have been used in the small and large scale tests.

As the technologies developed have to be cost effective, functional and adaptable to engineering design, an end-user board followed the project from the start and helped to define technical and application requirements. Moreover, a life cycle cost analysis, supplemented by a life cycle assessment has been performed in order to demonstrate the impact of the self-healing technologies on environment and economy.

## 1. INTRODUCTION

Reinforced concrete is designed to crack, but crack widths are limited to 0.2 to 0.4 mm depending on exposure class and type of concrete (reinforced or pre-stressed). Although these cracks do not impair structural stability, through-going cracks drastically affect liquid tightness. This is a major problem in tunnels and large underground structures, where cement hydration reactions and temperature/shrinkage effects in large concrete segments might result in the formation of early age cracks. Expensive preventive measures or repair works are needed right after construction. Furthermore, even if not through-going, cracks will allow faster penetration of aggressive liquids and gases, compromising the long-term durability of the structure. Current practice requires regular inspection, maintenance and repair, to ensure structural safety over the service life of the structure. These practices involve large direct and indirect costs, such as economic losses from traffic jams. Additionally, not all structures are easy to access for inspection and repair.

In their search to overcome these problems, researchers have been inspired by nature. Biological systems such as bones, skin or plants have the capacity to detect damage very quickly and have moreover the unique feature to repair the damage efficiently. It would be an enormous advantage if this concept could be translated to our engineering materials, such as concrete. The application of so-called “self-healing” concrete, which will in an autonomous way repair cracks, could reduce the maintenance costs drastically. Additionally, indirect costs such as due to traffic congestion can be avoided.

## 2. PROJECT OBJECTIVES

The overall objective of the project was to design, develop, test, apply and evaluate self-healing methods for concrete structures. Depending on the type of damage, another self-healing concept was envisioned. While static cracks (e.g. early age cracks due to shrinkage) can be filled with a non-elastic material, moving cracks (e.g. bending cracks in bridge beams) are preferably filled with elastic healing materials. This means that biogenic healing agents as well as polymeric healing agents (hydrogels and elastic polymers) have been considered.

### **OBJECTIVE 1: *Development of efficient self-healing techniques that enable concrete to regain liquid-tightness via bioprecipitation and application of hydrogels***

Incorporation of bacteria in concrete can enhance crack healing by production of  $\text{CaCO}_3$ , as a result of their metabolic activity and of subsequent chemical reactions including the metabolic products. While encapsulation of micro-organisms would help to increase their survival in concrete, the key element to have a successful self-healing is the choice of the bacterial strain. Promising results were obtained with micro-encapsulated bacterial spores, and although we were able to up-scale the procedure to produce axenic (pure) cultures of *Bacillus sphaericus* and their encapsulation, this healing agent is quite expensive for use in self-healing concrete. Hence, an enrichment selective process was designed that allows the production of a mixed culture (non-axenic) derived from low value agricultural by-products, with good ureolytic characteristics and capable to induce calcium carbonate precipitation. Furthermore, alkali-resistant spores of *Bacillus* and nutrients have been successfully incorporated in expanded clay particles. These particles serve as healing agent reservoirs for protection and immobilization of the biogenic healing agent.

Superabsorbent polymers (SAPs) are three-dimensional, crosslinked polymeric networks that are not soluble, but which can absorb large quantities of water. Due to their swelling properties, the synthesized SAPs incorporated in mortar immediately block the crack and prevent further ingress of water via this crack. Consequently, very high sealing efficiencies are already reached immediately after crack formation. Moreover, after a healing period, the crack can even close due to (mainly) precipitation of  $\text{CaCO}_3$  or ongoing hydration, leading to an even higher sealing efficiency. In order to reduce the uptake of water during concrete mixing, causing a decrease in workability and increase in macro pore formation (for mixes with relative high w/c ratios), and to seal the crack more efficiently, HEALCON partners proposed the following: (i) coating of the SAPs and (ii) development of synthetic superabsorbent polymers with improved swelling and pH sensitiveness.

In order to test the regain in liquid-tightness of the different self-healing systems, water flow tests and capillary water absorption tests have been designed and applied.

**OBJECTIVE 2: *Development of efficient self-healing techniques for bending cracks in concrete elements under dynamic loading, as solution to prevent future durability problems***

The use of encapsulated, commercial PU-based polymer precursors as healing agents has shown potential for efficient healing of cracked concrete in proof-of-concept specimens containing cylindrical glass capsules. These capsules break upon crack appearance and release their healing agent, leading to immediate closure of the crack (dispersion of the precursor and hardening in less than 48 hours). Self-healing based on an encapsulated precursor of a flexible polymer resulted in a stiffness regain of 35 % and a very effective sealing of healed cracks. Flexible polymers allow keeping cracks sealed even in the case of moving cracks, although sealing is disrupted after a crack movement above 50 % of the original crack width for the precursors studied. When subjected to multiple cycles of crack movement, disruption of the sealing is noticed for crack movements above 20%. Upscaling of the technique is taking place by using randomly dispersed capsules that, due to their specific geometry, can withstand the mixing process of concrete. Ongoing research focusses on the development of polymer precursors with increased resistance to crack movement and on alternative encapsulation techniques with polymeric tubes.

**OBJECTIVE 3: *Development of computer models to simulate the fracturing and self-healing mechanisms in order to refine lab tests and to ultimately scale the mechanisms to an industrial level***

Models were developed to provide evaluations and suggestions to partners for their developed self-healing system (e.g. evaluation of the self-healing efficiency and optimization of the mix design). Furthermore, the mechanical interaction between the capsules of the self-healing system and the cementitious matrix was studied. The main idea behind this was that different activation of the self-healing mechanism is needed, depending on the self-healing mechanism. Therefore, the mechanical properties (E-modulus, tensile strength) of carrier particles (in relation to the mechanical properties of the cementitious matrix) need to be tailored depending on the healing mechanism. The Delft Lattice model has been adopted to simulate the fracture procedure of mortar or concrete under typical loadings.

**OBJECTIVE 4:** *Development of non-destructive testing and monitoring techniques and combine existing ones to characterize the effects of different self-healing mechanisms in small and full-size specimens*

In this project the NDT techniques were mainly used to analyse the healing efficiency of concrete specimens. Therefore, specimens with all relevant healing agents have been prepared. For specimens with precursors of elastic polymers, it was shown that cracking as well as healing can be clearly monitored. With acoustic emission, concrete and capsule rupture and failure of the polymeric healing agent can be detected and localized. The ultrasonic transmission method has proved essentially effective for the determination of the crack depth and its propagation during all different states (initial, cracked, healed) of an experiment. Real-time monitoring of the evolution of ultrasonic waves allows following continuously the cracking and healing process.

For the large scale tests, it was decided to perform US measurements and use impact acoustic transmission techniques. Also long term monitoring techniques were used to measure the corrosion potential and electric impedance with embedded electrodes.

**OBJECTIVE 5:** *Development of a life-cycle assessment methodology to demonstrate the impact of self-healing technologies on the economy, society and environment*

A life-cycle assessment (LCA), considering the environmental impact and a life-cycle cost analysis (LCC), calculating the economic impact, have been performed for a hypothetical tunnel element, designed to be watertight. The 'reference' tunnel element contains a membrane for waterproofing and the 'alternative' solution is made of self-healing concrete. Analyses were done for the production phase (not the operation phase). During the operation phase, repair works should be taken into account and as the working life of the healing agents is not yet exactly known, there is a risk that crack injection is needed later on, also for the self-healing concrete. Moreover, it has to be noted that a considerable cost reduction for the alternative solutions is expected when the healing agents are manufactured at industrial scale.

**OBJECTIVE 6:** *Demonstration of the developed technologies in a real size structure and develop construction specifications for the use of self-healing products developed within the project*

The developed self-healing methodologies have been tested in large-scale elements (beams and slabs) under lab-scale conditions. A lot of efforts were made to upscale the production of healing agents. The self-healing agents, which have been incorporated in the elements were the biogenic healing agents and SAPs. Different techniques, including non-destructive testing, have been used to evaluate the self-healing performance. Currently, larger elements are made which will be exposed to conditions close to reality and possibilities to include the new technologies in actual concrete structures are examined.

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**REFERENCES**

Papers published within the framework of HEALCON and public deliverables of the HEALCON project can be consulted on the HEALCON website : [www.healcon.eu](http://www.healcon.eu).