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# Visualized tracing of crack self-healing features in cement/microcapsule system with X-ray microcomputed tomography

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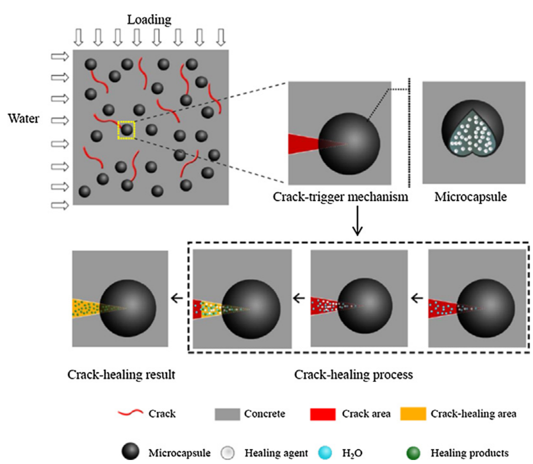
## HIGHLIGHTS

- A novel microcapsule based self-healing system is designed and synthesized.
- X-ray µCT can be applied to non-destructively monitor the crack-healing process.
- The microcapsule based self-healing system is feasible and effective.
- The extent of the self-healing process strongly depends on the transport of water.
- The healing system exhibits remarkable crack-healing property.

## GRAPHICAL ABSTRACT

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## ABSTRACT

A novel type of microcapsule-based self-healing material which holds promise for crack-healing of concrete in a marine environment is designed and prepared, in which the calcium sulfoaluminate cement (CSA) is used as the healing agent. In the present work, X-ray microcomputed tomography (X-ray µCT) is innovatively applied to study the crack-healing process of the microcapsules based self-healing system. The healing mechanism is further analyzed by means of scanning electron microscopy (SEM)/energy-dispersive X-ray spectroscopy (EDS). The experimental results demonstrate that the microcapsule-based self-healing system is feasible and effective. The initial cracks are dramatically restored with the fill of the hydration product brought about by the CSA and water. The extent and rate of the self-healing process strongly depend on the transport of water from the surface to the body of the cementitious materials. The healing efficiency is up to 82.60% according to the volume variation of the cracks.



## 1. Introduction

Cementitious material, such as concrete, is the most used material worldwide in civil engineering [1]. However, some inevitable drawbacks are present in this kind of materials. The most conspic-

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uous problem is the cracking caused by inappropriate curing, freeze-thawing, temperature gradients and mechanical loading, etc. Cracking can affect permeability which allows aggressive substances to penetrate deep into the concrete, and thus leads to the deterioration of cement matrix and the corrosion of reinforcement, particularly in marine environment [2–5]. Generally, cracks in concrete are mended by hand, but always need high maintenance and repair cost [6,7]. Accordingly, self-healing strategy is regarded as a potential solution to obtain a sustainable concrete [8–12].

Actually, cementitious materials have the innate autogenic ability to self-heal, as the rehydration of a concrete specimen in water can serve to kick-start the hydration process when the water reacts with pockets of unhydrated cement in the matrix [13]. However, the capacity for crack-healing in most common types of concrete appears to be limited [14]. Therefore, in order to enhance the crack-healing properties of concrete, extra healing agents which can be added to the cement-based materials are needed. Among the current studies of self-healing strategies, one of the potential alternatives to store healing agents is through microcapsule [15,16]. However, there are several key points of this method. First, the healing agent needs to be sealed in a microcapsule [17,18]. In addition, the geometry and texture of the microcapsule are critical to achieving a successful healing and it has been found that spherical microcapsules could reasonably satisfy this type of requirements in cementitious material [16,19]. Moreover, it is necessary to make sure that the microcapsules can survive during the mixing process and have a good bonding with the cement paste. In the end, the wall of the microcapsule can be ruptured, for example by cracks, and then the self-healing mechanism is triggered through the release and reaction of the healing agent in the region of the crack [20,21]. A successful novel attempt using organic microcapsules in cementitious materials is made at Shenzhen University by Xing and Dong et al. with promising results [22–27].

In this study, CSA is used as the healing agent for curing cracks occurring in concrete infrastructure in a marine environment. This is mainly because CSA can produce dense products after quick hydration process, which can help to heal the cracks in a short time [28]. Nevertheless, the high diffusivity in CSA-based samples can also be found due to the interconnected pores created among the hydration products [29]. The concept of the self-healing system is shown in Fig. 1. Under long-term loading and high-water pressure, cracking is inevitable for these brittle materials. Once the crack initiates and propagates, the embedded microcapsule at the tip of the crack will be ruptured. CSA inside the microcapsules is then released and reacts with water to heal the cracks. The releasing mechanism of CSA is also found by Qingliang Huang, et al, which helps to elaborate the concept of microcapsules based system [30]. Based on previous researches, the crack can be healed in a short period because the CSA reacts with water at a fast rate and most of the hydration heat evolution occurs between 2 and 12 h of hydration. Additionally, the main crystalline hydration products ettringite and monosulfate are formed together with amorphous aluminium hydroxide (Eq. (1) and (2)) [31]. Ettringite is a compound characterized by the following properties: (a) it has high surface energy and a specific surface area; (b) it has remarkable binding ability; (c) it has early onset of its mechanical strength [28]. All these properties help to improve the crack healing process.

$$C_4A_3S + 18H \rightarrow C_3A \cdot CS \cdot 12H + 2AH_3 \text{ (monosulfate formation)} \quad (1)$$

$$C_4A_3S + 2CSH_2 + 34H \rightarrow C_3A \cdot 3CS \cdot 32H + 2AH_3 \text{ (ettringite formation)} \quad (2)$$

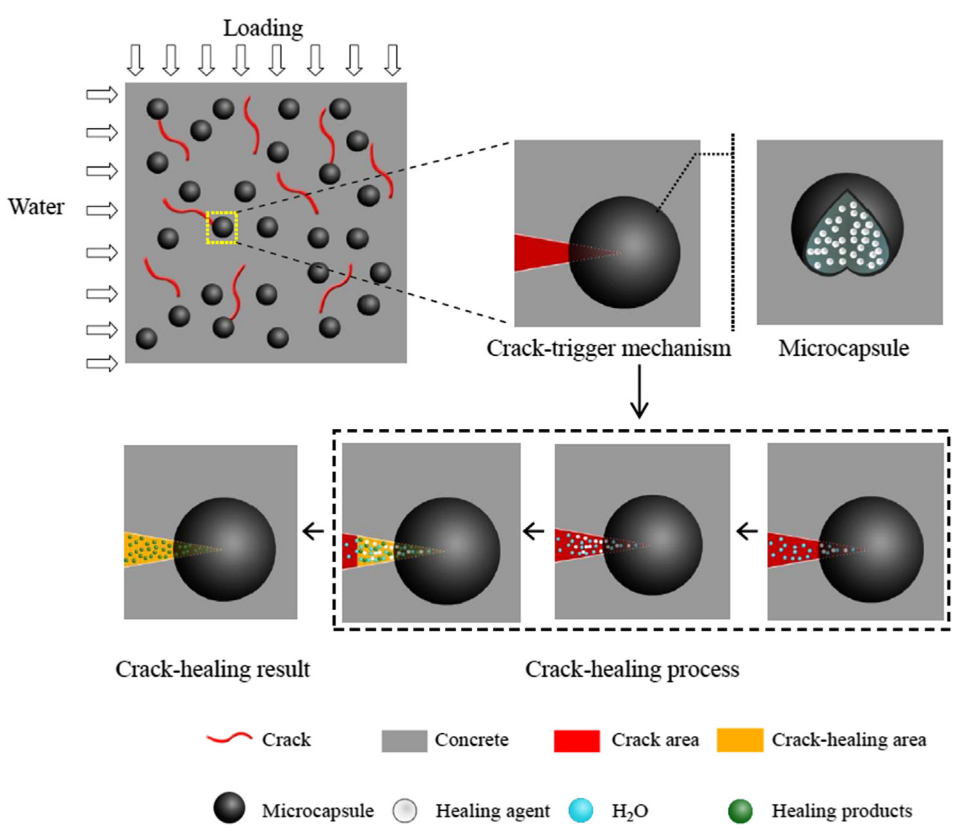


**Fig. 1.** Schematic illustration of the crack-healing process.