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Review

Robust evaluation of self-healing efficiency in cementitious materials – A review

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HIGHLIGHTS

- A comprehensive survey is presented on assessment methods for self-healing concrete.
- Application of assessment methods to various self-healing mechanisms is summarized.
- Four robustness criteria for evaluating self-healing efficiency are proposed.
- Different assessment methods are studied against robustness criteria.
- Major limitations of assessment methods are summarized.

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ABSTRACT

During the last decade, self-healing of concrete has attracted so much attention in the research community as a promising tool toward more durable and sustainable infrastructures. Although various self-healing approaches have been vastly studied, employment of different assessment methods in these studies has made it difficult to compare the efficiency of various self-healing mechanisms. This paper presents a review of test methods which have been commonly utilized to assess the efficiency of self-healing mechanisms in concrete. Three broad categories of assessment methods are considered, namely visualization and determination, assessment of regained resistance and assessment of regained mechanical properties. Moreover, as a pathway toward standardized evaluation of self-healing mechanisms, various assessment techniques are evaluated against four proposed essential criteria – reliability, quality of results, operational considerations and *in-situ* applicability.

Contents

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1. Introduction

Concrete is the most widely-used construction material throughout the world. One of the major issues with concrete is its relatively high vulnerability against micro-cracking. Unless they are efficiently detected and repaired, they can lead to bigger cracks overtime. This can have substantial negative effects on the durability and integrity of the concrete as well as the strength and serviceability of the whole structure. On the other hand, inspection, maintenance and repair of concrete structures using conventional methods may not be always efficient [1] and could be very costly. Annual cost of such procedures is estimated at about $20 billion in U.S. [1] while in Europe, it is around half of the total annual construction budget [2].

Over the last two decades, the concept of self-healing ability of concrete structures has been studied intensively and a number of reviews have become available on various self-healing approaches in concrete [3]. Approaches to self-healing in concrete can be broadly categorized into two main classes based on the mechanism of the healing; autogenous healing and autonomous healing. The efficiency of different approaches may vary significantly based on the general circumstances of the material, the composition of the cementitious matrix, the application and final purpose of the structure and etc. This, in turn, leads to various methods for evaluation of self-healing efficiency.

Many different assessment methods have been employed by different researchers to evaluate the healing efficiency of various self-healing approaches. A common criterion to classify these methods is based on what properties of the healed specimen are being investigated and evaluated [3]. Based on such criterion, three categories can be considered: visualization and determination, assessment of regained resistance and assessment of regained mechanical properties.

With emerging new approaches to achieve self-healing in cementitious materials, establishment of normalized testing procedures which enables comparison of different techniques and, in general, qualification of healing efficiency seems to be of great significance. In this regard, while a vast literature covers the underlying processes of self-healing concrete technology, there is a lack of significant studies focused on the assessment methods available for evaluating the efficiency of different self-healing mechanisms. Thus, a new challenge in the area of self-healing concrete technology can be introduced as setting common grounds toward a standardized evaluation of self-healing mechanisms in concrete. As an initial step toward standardized self-healing evaluation techniques, in this paper, the concept of *robust* assessment of the efficiency of various approaches to self-healing of concrete is proposed as a set of four essential criteria: reliability, quality of results, operational considerations and *in-situ* applicability.

The structure of the paper is as follows: in Section 2, the major approaches to self-healing of concrete are briefly studied. Then, major assessment methods which have been broadly employed in the literature to evaluate the efficiency of different self-healing approaches are investigated and categorized in Section 3, followed by introduction of robustness criteria for self-healing evaluation against which generic assessment methods for self-healing of concrete are evaluated in Section 4. Finally, conclusions are drawn in Section 5.

2. Self-healing approaches

Based on whether the healing process is originated naturally from the cementitious material or an artificial trigger is required to activate the process, approaches to self-healing can be categorised into two major classes, namely autogenous healing and autonomous healing.

2.1. Autogenous healing

Autogenous crack healing in concrete is associated with the self-healing properties resulting from the physical and/or chemical composition of the cementitious matrix. This process mainly relies on one or more of the following four mechanisms [13]: (1) formation of calcium carbonate from calcium hydroxide; (2) settlement of the debris and loose cement particles in presence of water; (3) hydration of unhydrated cementitious particles; (4) further swelling of the hydrated cementitious matrix (Fig. 1). While the hydration of unreacted particles has shown to be the main crack healing mechanism for young concrete [4], at later ages, formation of calcium carbonate becomes more prominent [5–8]. However, all mentioned mechanisms require the presence of water in order to be effective in crack healing.

The autogenous self-healing of concrete is only effective for small crack widths [5,9–11]. The maximum crack width healable by autogenous healing has been reported to be between 200 and 300 μm [5,9]. Several methods have been proposed to improve the effect of autogenous crack healing in concrete, including restriction of crack widths either by applying compressive forces [12–14] or by introducing fiber reinforcements in engineered cementitious composites (ECC) [6,7,15–25] and references therein, supply of water for ongoing hydration through employment of superabsorbent polymers (SAP) [26–30] or other internal water reservoirs, such as lightweight aggregates [31,32], promotion of the ongoing hydration and crystallisation by addition of certain agents to the cementitious matrix [12,33–48] and finally extension of the healing effect to both larger area and longer period of time by introducing polymer modified concrete (PMC) [49–53].