Construction and Building Materials 63 (2014) 108–118

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Feasibility of self-healing in cementitious materials – By using capsules or a vascular system?

Haoliang Huang [a,*], Guang Ye [a,b], Zhonghe Shui [c]

[a] Microlab, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands
[b] Magnel Laboratory for Concrete Research, Department of Structural Engineering, Ghent University, Technologiepark-Zwijnaarde 904 B-9052, Ghent (Zwijnaarde), Belgium
[c] School of Materials Science and Engineering, Wuhan University of Technology, Wuhan 430070, PR China

HIGHLIGHTS

- Healing agent released from capsules of various dosage and size was quantified.
- The effect of healing agent migration on self-healing was determined by modeling.
- Self-healing by using vascular systems to supply healing agent was evaluated.
- Self-healing realized by using capsules and vascular systems was compared.
- Ways to improve the efficiency of self-healing by using capsules were discussed.

ARTICLE INFO

Article history:
Received 3 December 2013
Received in revised form 12 March 2014
Accepted 2 April 2014

Keywords:
Self-healing
Calcium hydroxide solution
Capsules
Vascular systems
Cementitious materials

ABSTRACT

Objective: The aim of this paper is to investigate self-healing in cementitious materials with saturated $Ca(OH)_2$ solution as a healing agent, supplied by using capsules and a vascular system.
Materials and methods: Numerical simulation was performed to determine the efficiency of the supply of saturated $Ca(OH)_2$ solution by using capsules and consequently the efficiency of self-healing. The influence of capsule dosage and size was taken into account. Ultrasonic pulse velocity tests were conducted to evaluate the efficiency of self-healing of cracks with saturated $Ca(OH)_2$ solution supplied via a vascular system.
Results: The simulation results show that the efficiency of self-healing of cracks with saturated $Ca(OH)_2$ solution supplied by using capsules is very low. This is due to the fast absorption of healing agent by the bulk matrix and the low efficiency of the supply of healing agent by using capsules. Increase of capsule dosage and size can improve the healing efficiency as the amount of healing agent supplied to crack linearly increases with the capsule dosage and diameter. In comparison, the efficiency of self-healing of cracks with saturated $Ca(OH)_2$ solution supplied via a vascular system is much higher. This is because sufficient saturated $Ca(OH)_2$ solution is supplied to cracks for healing via a vascular system.

1. Introduction

Caused by external loading and time dependent effects, cracks are unavoidable in reinforced concrete structures. These cracks reduce the durability of reinforced concrete structures by creating preferential paths for aggressive substances. For this problem, manual repair is a common solution [1]. Although manual repair can prolong the service life of reinforced concrete structures, it has some limitation. For instance, even though the quality of such repairs has substantially increased in recent years, it is still recognized that realizing durable repairs is difficult. Most of these repairs can only last for ten to fifteen years [1]. Furthermore, it is difficult to repair some cracks which are not accessible, such as cracks in underground concrete structures [2]. Apart from these technical aspects, the cost of manual repairs is very high [3]. Moreover, if structures, like bridges and tunnels, have to be taken out of service for repair, the indirect costs caused by repair could be even higher than the direct costs of the repair itself [1]. This is a high financial burden for society.

Accordingly, it could be of significant benefit if concrete structures could heal the damage by themselves [2]. Self-healing of cracks in concrete structures has been attracting much attention in recent years. Many researchers have explored how to efficiently realize self-healing of cracks in concrete structures. Pioneer work was carried by Dry [4,5] in the 1990s, who used glass capsules and tubes to supply liquid adhesive to cracks for self-healing of cracks in concrete. Later, Li et al. [6] applied cyanoacrylate-filled

---

[*] Corresponding author. Tel.: +31 152784001; fax: +31 152786383.
E-mail address: haoliang.huang@tudelft.nl (H. Huang).

http://dx.doi.org/10.1016/j.conbuildmat.2014.04.028
0950-0618/

glass capsules, combined with the use of PE fibers to improve the self-healing efficiency. Recently, other encapsulated polymeric based healing agents were also investigated [2,3,7–11]. Apart from the polymeric based healing agents, self-healing of concrete with the help of bacteria and geomaterials was explored as well [2,12–16]. From these studies, it can be concluded that the healing agent and the way of supplying the healing agent to cracks are the key issues to guarantee the realization of self-healing in concrete structures. Regarding the healing agents, properties such as reaction rate, compatibility with concrete matrix, environmental effects and cost should be taken into account. According to the literature, polymeric based healing agents, such as cyanoacrylate [17] and methyl methacrylate [4], can heal cracks efficiently. The costs of these healing agents, however, are relatively high and some of them may cause environmental and health hazards. In comparison, water [18–25] or solutions such as Na_2FPO_3 solution [26] and $Ca(OH)_2$ solution [3], which are able to react with the concrete matrix, are usually cheaper and more environmentally friendly. In a previous study [27], the efficiency of self-healing induced with water or saturated $Ca(OH)_2$ solution was compared. It was concluded that in cement paste self-healing induced with saturated $Ca(OH)_2$ solution progressed faster than that with water. In this study, considering the low cost, environmental benefit and the good compatibility with the concrete matrix, saturated $Ca(OH)_2$ solution is used as healing agent in cementitious materials.

It is known that liquid healing agents can be supplied to cracks by using capsules [3,4,7,9–11,28–30] or a vascular system [5,7,29–32]. With respect to the use of capsules, a liquid healing agent is first encapsulated and pre-embedded in the matrix. Once the capsules are broken by cracks, the liquid healing agent can be released. Regarding the use of a vascular system, a concrete frame with glass tubes in it for self-healing was tested by Dry [33]. Glass tubes as the elements of the vascular system were embedded in the concrete structure during the construction. When cracks occur, the pre-embedded glass tubes were broken by the cracks and then the liquid healing agents were injected via the open end of the tubes. The liquid healing agents were absorbed into cracks due to capillary forces, because the crack width is much smaller than the diameter of the tubes (normally larger than 3 mm). As a result, self-healing was induced by using a vascular system to supply liquid healing agent to cracks.

From an engineering practice point of view it is still uncertain which method i.e., capsules or a vascular system, is the most appropriate to supply saturated $Ca(OH)_2$ solution to cracks for self-healing.

In order to provide guidance to engineering practice, the use of capsules or a vascular system to supply saturated $Ca(OH)_2$ solution to cracks for self-healing was investigated in this study. The structure of the paper is formulated in 7 sections. After the introduction, self-healing induced with saturated $Ca(OH)_2$ solution was simulated. Next, the filling fraction of cracks with reaction products versus the amount of saturated $Ca(OH)_2$ solution was determined by coupling the migration of $Ca(OH)_2$ solution from cracks into the bulk paste. In Section 4, the use of capsules to supply saturated $Ca(OH)_2$ solution to cracks was investigated. The amount of $Ca(OH)_2$ solution released from the capsules was calculated by means of a Monte Carlo Method [34]. Consequently, the filling fraction of a crack versus the dosage and size of capsules was determined. In this study, no experiments were carried out on the use of capsules for self-healing as the manufacturing of capsules were being investigated. In Section 5, studies were performed on the use of a vascular system to supply saturated $Ca(OH)_2$ solution for self-healing. Ultrasonic pulse velocity measurements were carried out to evaluate the efficiency of self-healing. Discussion on these two methods for self-healing in cementitious materials was given in Section 6. At the end of this paper, conclusions were drawn and recommendations for self-healing by using capsules or a vascular system to supply saturated $Ca(OH)_2$ solution to cracks were proposed.

2. Modeling of self-healing induced by saturated $Ca(OH)_2$ solution

2.1. Mechanism of self-healing induced by saturated $Ca(OH)_2$ solution

The mechanism of self-healing is schematically illustrated in Fig. 1. When the unhydrated cement particles in the cement paste matrix come into contact with saturated $Ca(OH)_2$ solution, the unhydrated cement clinker dissolves and Ca^{2+} ions are gradually released. In addition, $SiO_2(aq)$ are released as well. Because the $Ca(OH)_2$ is already saturated in the solution, once the Ca^{2+} ions are released from the unhydrated cement, solid $Ca(OH)_2$ (portlandite) is immediately precipitated in the crack [35]. When the concentration of $SiO_2(aq)$ reaches a certain value, C–S–H is formed as well.

When cracks are filled with $Ca(OH)_2$ solution, CO_2 coming from the atmosphere can only dissolve into the solution inside cracks through the crack mouth. The concentration of CO_3^{2-} inside cracks will be very limited because of the narrow crack mouth. Therefore, in this stage the carbonation of $Ca(OH)_2$ solution inside cracks is neglected. The main mechanism of self-healing induced by $Ca(OH)_2$ solution is the precipitation of portlandite accompanied with the further hydration of unhydrated cement. However, when the cracks are not filled with $Ca(OH)_2$ solution anymore, the newly formed reaction products inside the crack is exposed to the atmosphere. Carbonation of these newly formed reaction products progresses gradually. In this study, only the healing process in saturated $Ca(OH)_2$ solution was studied. The carbonation was considered as a subsequent stage which will be studied in the future.

2.2. Simulation of self-healing induced by saturated $Ca(OH)_2$ solution

In previous studies [36,37], a reactive transport model based on a diffusion law and a thermodynamic law was developed to

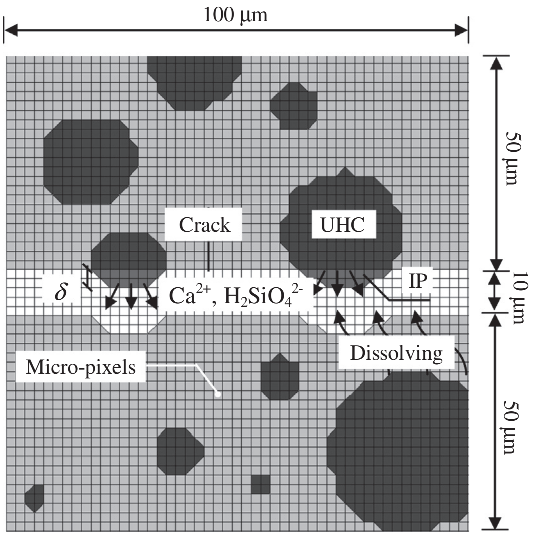

Fig. 1. Schematic of the microstructure for the simulation of self-healing. UHC refers to unhydrated cement; IP refers to inner products: the hydration products occupy the original space of cement that has reacted; δ refers to the penetration depth (see Section 2.2.1).