Construction and Building Materials 87 (2015) 1–7

Contents lists available at ScienceDirect

Construction and Building Materials

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

Factors affecting crack repairing capacity of bacteria-based self-healing concrete

Mian Luo, Chun-xiang Qian *, Rui-yang Li

School of Materials Science and Engineering, Southeast University, Nanjing 211189, China
Research Institute of Green Construction Materials, Southeast University, Nanjing 211189, China

HIGHLIGHTS

- Bacteria-based self-healing concrete was developed.
- Bacteria induced precipitations at cracks were analyzed by SEM and XRD.
- The crack self-healing effect under different conditions were studied.
- The image characterization method was used for crack-healing quantification.

ARTICLE INFO

Article history:
Received 12 December 2014
Received in revised form 26 March 2015
Accepted 31 March 2015
Available online 11 April 2015

Keywords:
Concrete
Self-healing
Crack width
Curing ways
Cracking age
Water permeability

ABSTRACT

Bacteria-based self-healing concrete is a relatively new technique, therefore it is important to gather more results in simulate real conditions before applied on a bigger scale. In the present study, bacteria-based self-healing concrete was developed by adding the microbial self-healing agent which has the potential to improve self-healing capacity mainly by bacteria induced mineral precipitations. The precipitations formed at the cracks surface of the cement paste specimens were analyzed with Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Spectrometer (EDS), and then examined by X-ray Diffraction (XRD). Moreover, the influence of crack width, curing ways and cracking age on the crack self-healing of cement paste with microbial self-healing agent was researched by the characterization methods of area repair rate and anti-seepage repair rate. The results showed that the microbial self-healing agent could be used to achieve the goal of concrete crack self-healing. The precipitations formed at the cracks surface were calcite, which appeared lamellar close packing morphology. However, the capacity of concrete crack self-healing depended on many factors. The crack was more and more difficult to be repaired with the increase of average crack width and the repair ability of microbial repair agent was limited for specimens with crack width up to 0.8 mm. Water curing was shown to be the best way for bacteria-based self-healing concrete. In addition, the crack healing ratio of specimens dropped significantly along with the extension of cracking age. When the cracking age was more than 60 days, the crack healing ratio was very small. The results above suggested that the optimal conditions were needed for the practical application of microbial self-healing agent.

1. Introduction

Concrete as a structural material received extensive use all over the world during the 20th as well as the 21th centuries. The rapid development of ready-mixed concrete is one of the important signs of concrete technological progress and overall quality improvement, but there are some new problems. The most prominent problem is the higher probability of cracking caused by non-load factors due to low tensile strength of concrete, such as shrinkage cracks, thermal cracks and chemical reaction cracks. Cracking increases the probability of ingress of aggressive substances into the concrete, endangering the durability of the material. Usually, cracks are mended by hand, which is unsatisfactory because cracks are often hard to detect and the maintenance and repair cost is high. Accordingly, self-healing of cracked concrete would be highly beneficial and researching on self-healing concrete has been widely carried out [1–6].

* Corresponding author at: School of Materials Science and Engineering, Southeast University, Nanjing 211189, China.

E-mail addresses: cxqian@seu.edu.cn, cquluomian@163.com (C.-x. Qian).

http://dx.doi.org/10.1016/j.conbuildmat.2015.03.117
0950-0618/

Self-healing of concrete is actually an old and well known phenomenon [7,8]. However, the capacity for crack-healing in most common types of concrete appears to be limited [9,10]. Bacteria induced mineral precipitation has been proposed as an alternative and environmental technique to improve the capacity of concrete crack-healing in recent years [11–14]. Jonkers and coworkers first proposed the use of bacteria induced mineral precipitation technology to strict self-healing of concrete crack, for which the healing process occurs without human intervention [15,16]. In their research, the specific mechanism of crack-healing is based on concrete matrix-incorporated dormant but viable spores of specific alkali-resistant bacteria which, after activation by crack-ingress water, produce inorganic mineral precipitates by conversion of organic precursor compounds. Experimental results showed crack-healing of up to 0.46 mm-wide cracks in bacterial concrete but only up to 0.18 mm-wide cracks in control specimens after 100 days submersion in water [17]. Wang et al. applied microcapsules to encapsulate Bacillus sphaericus spores for self-healing concrete [18]. The results indicated that the maximum crack width healed in the specimens of the bacteria series was 970 μm, about 4 times that of the non-bacteria series. The overall water permeability in the bacteria series was about 10 times lower than that in non-bacteria series. Many research results showed that bacteria carrier protective and water environment were needed for this biotechnology application [19–21]. In practical cases, the conditions are more complex compared to laboratory. The cracking of concrete maybe occur in different age and crack width varies a lot. Due to the harsh environment inside the concrete, the bacteria would die over time despite encapsulated or immobilized in a protective carrier. In addition, the differences in environmental conditions in practical engineering are great, some immersed in the water for a long time, some in moist environment and others in wet–dry condition. The real environment would have a great influence on the crack repair effect. Bacteria-based self-healing concrete is a relatively new technique, it is important to gather more results in simulate real conditions before applying self-healing concrete on a bigger scale.

In the present study, bacteria-based self-healing concrete was developed by adding the microbial self-healing agent which has the potential to improve self-healing capacity mainly achieved by bacteria induced mineral precipitations. The influence of crack width, curing ways and cracking age on the crack self-healing of cement paste with microbial self healing agent was researched by the characterization methods of area repair rate and anti-seepage repair rate. Moreover, the optimal conditions for the practical application of microbial self-healing agent were discussed.

2. Materials and methods

2.1. Microbial self-healing agent preparation

Spore-forming alkali-resistant bacteria were used for this study. The bacteria was cultured in liquid medium containing 5.0 g peptone and 3.0 g yeast extract per liter of distilled water (pH = 7.0), which was autoclaved at 121 °C for 25 min. After inoculation on laminar flow, the medium was incubated at 30 °C on a shaker at 170 rpm for 24 h. The microbial self-healing agent consisted of substrate and bacteria. Bacterial cells were harvested by centrifuging the 24 h old grown culture and were re-suspended in distilled water. The concentration of bacteria in the suspension was 10^9 cells/mL.

2.2. Preparation of cement paste specimens

Two kinds of cement paste specimens were prepared by mixing ordinary Portland cement, self-healing agent and tap water. The mixing proportion is shown in Table 1. Cylindrical specimens with dimensions of 75 × 35 mm (diameter × height) were used for water permeability test and prismatic specimens with dimensions of 40 × 40 × 160 mm were used for the image characterization of crack healing efficiency. After curing for 24 h specimens were unmolded and kept in standard curing room for further curing.

Table 1
Mixing proportion of 1 L cement paste.

Cement (g)	Water (g)	Substrate (g)	Bacteria liquid (mL)
1502	491	30	30

2.3. Creation of artificial cracks

In order to simulate the real state of concrete crack and reduce the influence due to crack differences, two methods were explored to produce cracks. For prismatic specimens, crack width was controlled by the embedded method (Fig. 1). First, the prismatic specimens were wrapped with adhesive tape except the sides needed to form cracks in order to keep the specimens integrity. Then the specimens were loaded on compression test machine. When the surface appear visible micro cracks, the loading was stopped. After that, different diameter nails were embedded in microcracks at both ends in the specimen surface to form different width cracks varies from 0.1 mm to 1 mm, which depended on the diameter of the nail. The cracks on prismatic specimens formed by embedded method were shown in Fig. 2. For cylindrical specimens, the compression test (loading speed 0.5∼0.8 MPa/s) was used to make crack, whose crack width is in the range of 0.1–0.5 mm.

2.4. Self-healing incubation conditions

For crack-healing quantification under different crack width, the prismatic specimens were taken out after 21 days curing, and then cracks of different width were created in the specimens by the method in Section 2.3. Then the treated cracked specimens were immersed in tap water in a plastic basin which was kept open to the atmosphere during the whole repair period. Meanwhile, oxygen was passed into the water constantly. For crack-healing quantification under different curing ways, the cracked cylindrical specimens were subjected to three incubation conditions: (1) 25 °C, immersion in water; (2) 25 °C, 90% RH; (3) 25 °C, wet–dry cycles. During one wet–dry cycle, the specimens were immersed in water for 12 h and were then exposed to air for 12 h. For crack-healing quantification under different cracking age, the cylindrical specimens were taken out after 7, 14, 28, 60 and 90 days curing, respectively. Then the cracks with an average width of 0.3 mm were created by the method in Section 2.3 and were immersed in tap water for incubation.

2.5. Self-healing effect characterization methods

The precipitations formed at the cracks surface of the cement paste specimens were analyzed with Scanning Electron Microscope (SEM) equipped with an Energy Dispersive X-ray Spectrometer (EDS), and then examined by X-ray Diffraction (XRD). In addition, two methods were used to characterize the crack healing efficiency. The image characterization method was used for the prismatic specimens and the water permeability test characterization method was for cylindrical ones.

The prismatic specimens were removed from water every few days to observe and record the changes of cracks width using the digital camera. The image processing of specimen surface cracks before and after healing were carried out. Then, the number of crack area pixel dot for specimens before and after healing was counted by setting the crack area threshold gray level for 115. The area repair rate was

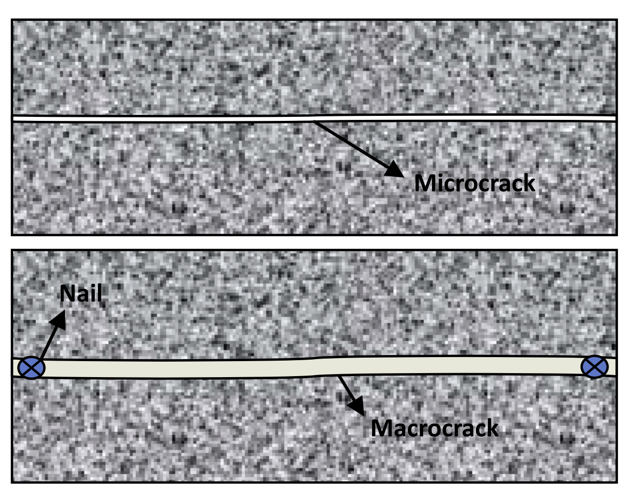

Fig. 1. Cracks creation process by embedded method.