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Effects of self-healing cracks in bacterial concrete on the transmission of chloride during electromigration

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HIGHLIGHTS

- The effects on transmission of chloride were test through multiple methods.
- The method of electromigration was used to accelerate the transmitting of chloride.
- The microbial self-healing cracks could impede the transmission of chloride.

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ABSTRACT

The microbial self-healing concrete has been a new technology to repair cracks, the former study showed that the precipitated $CaCO_3$ could fill the cracks and reduce the permeability coefficient of cracks. On this basis, the impacts on resisting transmission of chloride were studied to evaluate the protective effects of microbial self-healing cracks, through multiple characterization methods such as electrochemical test, visual examination of cracks surface, weight-loss ratio of reinforcements and chloride ion content. Besides the method of electromigration was used to accelerate the transmission of chloride. The results show that the microbial self-healing cracks can indeed impede the transmission of chloride in cracks and have protective effects for reinforcements in the concrete.

1. Introduction

Concrete materials have the advantages of high compressive strength, better fireproofing and durability, easiness in obtaining materials [1], which have been widely used in many practical projects like water conservancy and hydropower, traffic, industrial and civil construction. They have become one of the most extensively used civil engineering materials. But during the preparation and usage of concrete, the external loads and other factors can result in loosing and spalling on the surface, seriously making cracks in the concrete [2]. The cracks will reduce the capacities of anti-permeability, anti-chloride-corrosion and anti-carbonization greatly, which can make the corrosion of interior reinforcements much easier and lower the carrying capacity and durability of structure. If the repair of concrete cracks isn't completed in time, it will affect the normal use of concrete structure, resulting in total destruction and even collapse.

The traditional repairing methods are passive in most cases. They have complex technology, high cost and even some destructive effects on the environment, which can't satisfy the requirement of modern intelligence and multifunction for concrete materials [3]. In 1995, Gollapudi et al. first proposed the method of using biology progress to repair cracks and got a bran-new solution for the problem [4]. Microbial self-healing methods mainly utilize the metabolism of bacteria to induce mineral precipitation. They have the advantages of simple technology, low cost and free of contamination, which have become the research hotspot [5–9].

Bacteria induced mineral precipitation has been proposed as an alternative and environmental technique to improve the capacity of concrete crack-healing in recent years [10–12]. For the self-healing effects of microbial self-healing methods, Wiktor et al. applied contrast test to the self-healing specimens and the control. The results indicated microbial self-healing concrete had more mineral precipitation and could repair wider cracks (470 μm), while only 210 μm width of cracks was in the control [13]. Luo

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et al. prefabricated 0.3 mm cracks in the specimens. They found that the microorganism repaired plenty of cracks in 5 days and could fill the surface of cracks completely in 20 days [14]. In their other researches, the bacterium loaded by pottery sand could repair maximum width of 1 mm. They also found that maximum $CaCO_3$ were precipitated in the opening of cracks and mainly concentrated on the area of 1.5 mm depth from the surface of cracks [15]. In addition, the changes of permeability coefficient before and after the healing of cracks can characterize the remediation effect. Wang et al. verified that microbial self-healing concrete was able to reduce the permeability coefficient of cracks, especially in the initial 24 h [16]. In the research of Tittelboom et al., it also showed that after using microbial self-healing agent to repair cracks, the anti-permeability and durability of concrete specimens were improved greatly [4]. It demonstrates that microbial self-healing technology can make repairing effects on the concrete cracks to some degree, but how much the real value of repairing effects and the effect on resisting the transmission of chloride, still need a further research.

In this study, we mainly used the previous microbial self-healing technology of our research group to test the influence of self-healing cracks on the transmission of chloride, then assessed the actual contribution for protecting reinforcements. In order to accelerate the transmission of chloride, we adopt the method of electromigration. Besides, the reinforcements were imbedded in the specimens to further study the protective performance under the effects of self-healing cracks.

2. Materials and methods

2.1. Microbial self-healing agent

Microbial self-healing agent consisted of two parts: bacteria powder and substrate. Bacteria power was Paenibacillus mucilaginosus. Cultivation of Paenibacillus mucilaginosus was conducted in sucrose culture (10 g of sucrose and 3 g of sodium hydrogen phosphate dissolved in deionized water to 1 L, and the pH value was adjusted to about 7.0) at 35 °C for 24 h. Bacteria powder was made from the above bacteria liquid by freeze drying process. The appropriate temperature of Paenibacillus mucilaginosus growth is 10–40 °C, while the pH value is 7.0–9.0.

2.2. Preparation of cement mortar specimens

There were two kinds of cement mortar specimens, the microbial self-healing and the control. The microbial self-healing specimens were prepared by mixing ordinary Portland cement, sand, self-healing agent and water. The mixing proportion as shown in Table 1. The control specimens had no self-healing agent so without subjection to bio-deposition. The dimensions of specimens were all 50 mm × 50 mm × 200 mm. There was a 10 mm diameter reinforcing steel bar with acid dipping treatment imbedded in the middle, the ends of the steel bar and the location of linking wires were sealed with epoxy resin.

2.3. Creation of artificial cracks and curing condition

In order to simulate the real situation of concrete cracks and reduce the influence due to the difference of cracks, we used the method of presetting the steel sheets in the mortar while making the specimens. The width of steel sheets was 40 mm, thickness was 0.2 mm and they must inserted vertically in the mortar with the depth of 20 mm and separation distance of 40 mm, as shown in Fig. 1. Take off the steel sheets at the final setting time of mortar, remove the form after one day and then put the specimens into standard curing room (20 ± 2 °C, RH > 95%) for

Table 1
Composition of self-healing specimens.

Material	kg/m^3
Ordinary Portland Cement	600
Water	300
Sand	1800
Substrate	12
Bacteria powder	1.2
w/c	0.5

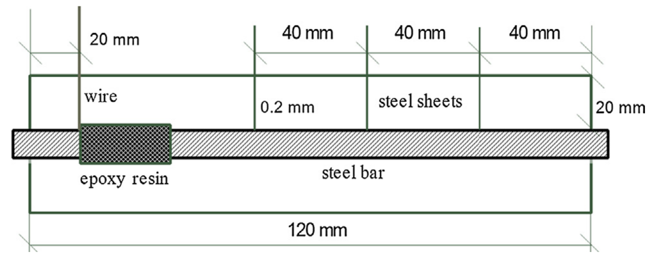

Fig. 1. The schematic of making cracks by steel sheets.

3 days. After that, the self-healing specimens were put into the 30 °C water and kept 21 days to ensure that the cracks would be healed effectively in the self-healing environment and the control specimens were in the same environment for the contrast. Those specimens representing the cracks before being healed were put in the standard curing room for 24 days at the same time.

2.4. Electromigration accelerated transmission of chloride

The method of using electromigration to accelerate the transmission of chloride is connecting a DC electrical source between the chloride solution and the reinforcing steel bar to produce an electric field among them. The chloride will invade into the specimen more quickly under the effect of the electric field, achieving the purpose of accelerating the transmission of chloride. We redesigned the electromigration device from other study [17]. The working device as shown in Fig. 2.

In the device, the reinforced specimens were immersed in the 3.5% NaCl solution (to simulate the seawater environment). The wires in the reinforced specimens were linked with the positive pole of the DC source. The stainless steel mesh with 6 mm square hole was placed above the specimens and connected with the negative pole of DC source by the wire. During the process of electromigration acceleration, the exterior voltage applied in the specimens would make abundant of heat. The degree of fever depends on the applied voltage and the resistance of cement materials. Those heat is harmful that can cause the transform of the microstructure in the cement-based materials and make the specimens damaged in a certain degree [18]. Therefore, the voltage of DC source used for electromigration acceleration can't be too high. Considering the problem of voltage and the test time, we chose 15 V as the voltage of DC source in the study. Because the water evaporation during the test may change the concentration of NaCl solution and lower the liquid level, we should always check the amount of solution during the process of electromigration. Keep the solution level above the stainless steel mesh to assure an effective electric circuit between NaCl solution and the steel bar in specimens.

2.5. Multiple characterization methods to evaluate the effect on chloride transmission

During the process of electromigration accelerating the transmission of chloride, the chloride reaching the surface of steel bar would induce the corrosion of reinforcements constantly. Therefore we can monitor the condition of steel bar corrosion to assess the degree of chloride transmission. Electrochemical test method is

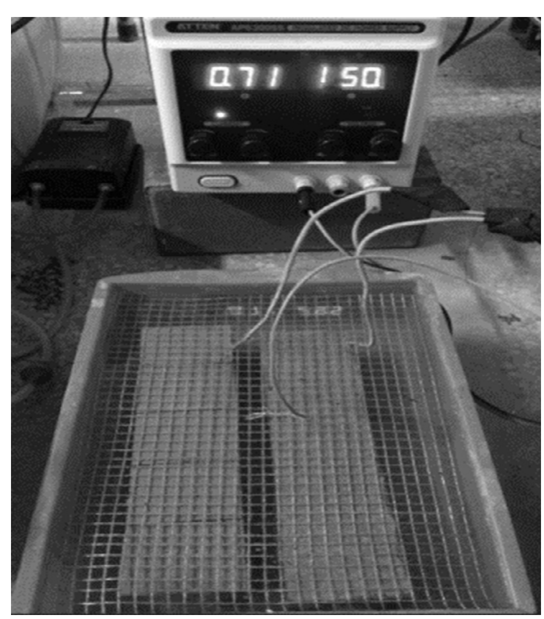

Fig. 2. The device of electromigration accelerated transmission of chloride.